Specification and Installation of a Robotic System to Improve the Production Efficiency of a Cutting Station

Heitor Dutra de Assumpção - 46690

Dissertation presented to the School of Technology and Management of Bragança to obtain the Master Degree in Industrial Engineering. Work developed during the double degree exchange program between the Polytechnic Institute of Bragança (IPB) and the Federal Technological University of Paraná (UTFPR).

Work oriented by:
Prof. Dr. Paulo Jorge Pinto Leitão
Prof. Dr. Marcos Banheti Rabello Vallim

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Dedication

I dedicate this work to everybody that helped me finish this project in one way or another, in special to my parents, Ana Cristina and Gilmar, my siblings, Giovani, Maximiliano and Tainá, my girlfriend, Nadya, professors and friends.

Acknowledgement

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To the professors of IPB and UTFPR, and to each employee of IPB, UTFPR and Catraport that were part of my development as student and researcher.

My friends that helped me in one way or another during the development of this work.

My family and my girlfriend for all the support and patience while I was abroad.

Abstract

One of the main technologies in Industry 4.0 are collaborative robots (*cobot*), which allow humans to work alongside them while respecting the necessary safety standards. The use of robots in industry is generally done to improve production, quality, reduce repetitive efforts and heavy manual labor. In order to save time and, consequently, money.

With this, the Catraport company presented the problem of automating a cutting station consisting of two machines. In the development of the automated solution, simulations were used to analyze which would be the most viable option for the company.

The company chose the hybrid solution formed by a robot and a worker. With the requirements defined, they purchased the robot, which they required to be a *cobot*. The model is the UR-10e, from Universal Robots, and also, as accessories, the adaptive gripper and the wrist camera, both from Robotiq.

After the purchase, the hardware part of the robot was installed and the software for the accessories was configured. With this, the visual recognition of the part was calibrated to identify its position, the gripper was adjusted to better fit the piece and possible solutions to position the parts in the exit box.

For the last step it was necessary to develop an individual programming case for each piece, because they have shapes that do not allow a simple fit between them. It was also used a resource of the camera to identify tags, which was used for the system to recognize the position and orientation of each pallet.

Keywords: Collaborative Robots; Automation; Simulations.

Resumo

Uma das principais tecnologias da Indústria 4.0 são robôs colaborativos (*cobot*), que permitem o trabalho ao lado de humanos respeitando as normas de segurança necessárias. O uso de robôs na indústria é geralmente feito para melhorar produção, qualidade, reduzir esforços repetitivos e trabalhos manuais pesados. De forma a economizar tempo e, consequentemente, dinheiro.

Com isso, a empresa Catraport apresentou o problema de automatizar uma estação de corte composta por duas máquinas. No desenvolvimento da solução automatizada, foram utilizadas simulações para a análise de qual seria a opção mais viável para a empresa.

A empresa optou pela solução híbrida formada por um robô e um trabalhador. Com os requisitos definidos, fez a aquisição do robô, que eles tinham como exigência ser um *cobot*. O modelo é o UR-10e, da Universal Robots, e também, como acessórios, a garra adaptativa e a câmera de pulso, ambos da Robotiq.

Após a compra, a parte de hardware do robô foi instalada e os softwares para os acessórios configurados. Com isso, o reconhecimento visual da peça foi calibrado para identificar sua posição, a garra foi ajustada para encaixar melhor na peça e possíveis soluções para posicionar as partes na caixa de saída.

Para a última etapa foi necessário desenvolver um caso de programação individual para cada peça, pois elas possuem formatos que não permitem um encaixe simples entre elas. Também foi utilizado um recurso da câmera de identificar tags, que foi utilizado para que o sistema reconhecesse a posição e orientação de cada pallet.

Palavras-chave: Robôs Colaborativos; Automatização; Simulações.

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Acronyms

CAD Computer-Aided Design.

CeDRI Research Centre in Digitalization and Intelligent Robotics.

CPS Cyber-Physical Systems.

DGS-PT *"Direção Geral de Saúde"*.

HRI Human-Robot Collaboration.

ICT Information and Communication Technologies.

IoT Internet of Things.

IPB Instituto Politécnico de Bragança.

IPB Polytechnic Institute of Bragança.

ISO International Organization for Standarization.

RFID Radio Frequency Identification.

ROI Return Of Investment.

RSI Repetitive Strain Injuries.

UTFPR Federal Technological University of Paraná.

UTFPR Universidade Tecnológica Federal do Paraná.

Chapter 1

Introduction

Industries have constantly been advancing to increase production, get better results, and always try to find a way to improve the actual manufacturing used. Industry 4.0 aligns the automated systems from the third industrial revolution with the available technologies that can collect and share data from different type of sensors and use them to find the best approach for companies.

One of the components of this revolution is collaborative robots (cobots), a sort of industrial robot with safety specifications that allow cooperative work with humans (i.e., capability to share the same workspace). Robots are used to automate manufacturing systems to improve production and prevent injuries to the employees by performing repetitive tasks or handling sharp objects.

In this context, Catraport, a company placed in the industrial zone of Mós (Bragança, Portugal) that produces components for the automotive industry using stamping machines, developed the idea to automate a cutting station to increase the number of produced pieces with the use of a collaborative robot. For this purpose, the main scope of this project was to study the viability of automating such a station using a robotic system, covering the simulation and design phase, as well as the installation in the factory plant.

1.1 Objectives

The main objective of this thesis is to study and develop a robotic solution to increase the efficiency of a cutting station for metallic pieces by introducing a robot to the system. The solution aims to automate one machine that represents a bottleneck in the production environment. This work pretends to use the robot to replace the workers and to improve the process.

With the main objective in mind, the problem will be divided in the following specific assignments:

- Study of the existing systems and analyze the robotic system requirements.
- Understand and get the needed knowledge in robotic simulation software.
- Development of the robotic solution in the simulation software environment.
- Perform the economic study to develop the robotic solution.
- Install, test, and validate the robotic solution in the factory plant.

1.2 Document structure

After this short contextualization presented in this chapter, Chapter 2 is related to the state of the art in the field of the work, comprising a description of the relevant related concepts and technologies. Chapter 3 presents a description of the case study, its requisites and needs. Chapter 4 describes the development of the robotic simulations aiming to study the proper solution for the case study. Chapter 5 is devoted to describe the installation of the robotic solution in the factory plant of the case study. Lastly, Chapter 6 presents the conclusions of the developed work and points out the future work.

Chapter 2

Related Work

This chapter briefly describes the related work in the field of robotics and simulation according to the development of an automated solution.

2.1 Industry 4.0

The Fourth Industrial Revolution is the first manufacturing transformation that is not related to the appearance of new technologies in an industrial environment [1], is the digital transformation of the factories and productions. It is a concept that levels individualization and virtualization across different technologies.

First introduced in Germany, 2011, the term refers to the integration between manufacturing operations systems and Information and Communication Technologies (ICT) - especially the Internet of Things (IoT) - forming the called Cyber-Physical Systems (CPS) [2]. With this integration, the systems can exchange data, making it is easier to reduce set-up times, developing and production cost and times, have optimal decisions, and increase fabrication. The main goals of industry 4.0, according to [3], are:

1. Allow cross-organizational networking and integration.
2. Integrate digital and actual world (CPS).
3. Guarantee operational safety, data privacy and IT security.

4. Flexibility
5. Training.
6. Efficiency.

This concept adds value by supporting physical and mental abilities, enables flexible careers, and, by optimizing production, also optimizes the use of resources, attending efficiently to consumers' requests. It is characterized by connecting the automation levels of the third revolution, using technologies like IoT, cloud computing, big data, artificial intelligence, human-machine interface, augmented reality, additive manufacturing, and collaborative robots.

Other important points about this concept are its design principles, that are [4] interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity. The first is the ability to make a continuous information flow between all levels. The following description is "a virtual copy of the physical world is created", which means visualizing the real environment in a virtual platform. The third element is distributing the technologies and responsibilities, not leaving the operation only in a specific central or machine. According to a connected process, the next subject is to communicate the systems in real-time to make the production runs appropriately. The upcoming topic is an overview of "customer centered", where the Smart Factories vision aggregates the technologies. Finally, the last is a system that can be easily adjusted to the current production.

The benefits of Industry 4.0 are to make manufacturing faster, more efficient, and more adaptable to the customer. Nevertheless, also the warning is to control the security of all the systems and data available, making sure that nothing is leaked or invaded.

Besides these principles and goals, some fundamental concepts in a wide range refer to Industry 4.0 [5]. They are Smart Factories, Cyber-Physical Systems, self-organization, adaptation to human needs, and corporate social responsibility. In particular, the description of virtualization principle refers to CPS, that can monitor the physical process, so then it can interact with the computations and vice versa. The development of CPS is in its third generations. The first uses identification technologies (i.e., RFID tags), storage, and analytic to a central monitor, the second with sensors and actuators using a limited range of functions. The actual stores and analyzes data, use multiple sensors and actuators, and everything is connected thru network [6].

A CPS is designed in three phases: modeling, design, and analysis. They are distributed, decentralized, and semi-autonomous and interconnect the computation, communication, and control [7]. In Figure 2.1 it is exemplified the production network according to a CPS.

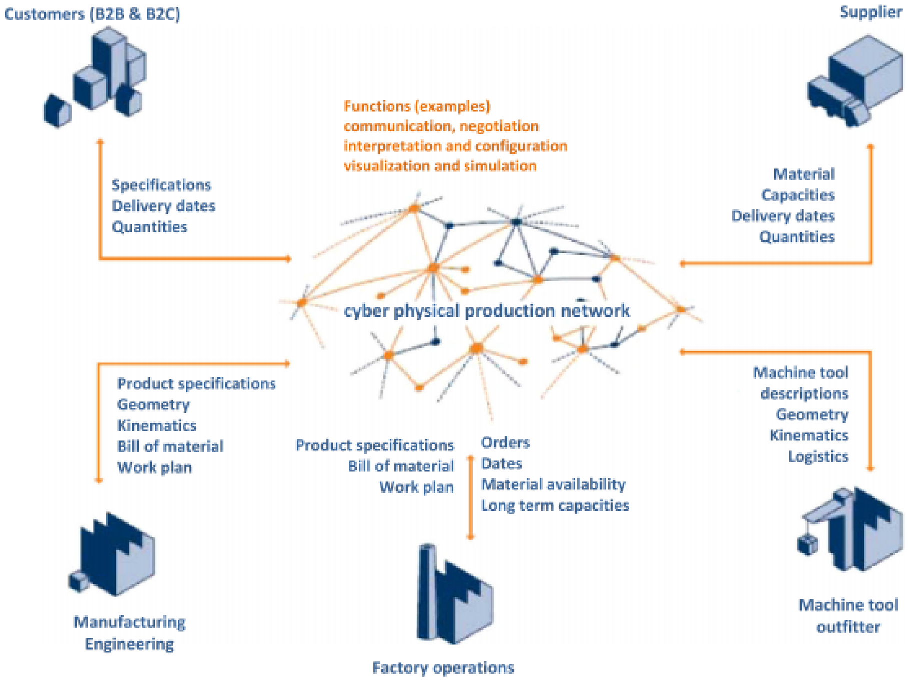


Figure 2.1: Cyber-Physical Systems [8].

The exemplified system shows the operating of a plant using CPS. It is possible to notice the interconnection and communication between the processes.

2.2 Robotic systems

Following the advances in sensors, wish to improve production and communications, the companies decide to automate their manufacturin for faster developments. The systems usually perform processes like transporting, assembling, and other tasks that or are repetitive or heavy.

By performing repetitive tasks, it is usual to appear Repetitive Strain Injuries (RSI). This is a way to classify injuries to the musculoskeletal systems caused by workplace conditions. It generally includes repetitive and forceful motions, static muscle loan and mechanical stress, vibration and temperature extremes, and awkward postures from improperly designed equipment [9].

The most common injuries are tendon-related, muscular, joint, and neurovascular/-vascular disorders and peripheral-nerve entrapment. According to the report about occupational injuries from *"Direção Geral de Saúde"* (DGS-PT) [10], the activities responsible for the significant accidents are movement, manual transport, work with manual tools, and object manipulation. So, this report shows the problems and dangers of manipulating objects in an industrial environment.

Due to all the problems for the employees, automation is a solution to avoid workers' illness, improve quality and manufacturing. In the process of automating a production, robots are used to perform the tasks related to the causes of RSI due to their ability, speed, and precision in executing repetitive jobs.

Therefore, the participation of a human operator in an assembly line is expected for a long time, whether for performing some assembly tasks or coordinating the line process. With both robots and humans, it is possible to have the advantages of each. So the first can take care of the monotonous and strenuous tasks, guaranteeing quality and keeping the conditions for the worker more ergonomic since he will not be needed to handle heavy weights, hazardous parts [11]. While the employee can focus on tasks that need his/her unique skills, like solving a problem or even help in another production sector.

This type of system is classified as Human-Robot Collaboration (HRI). A HRI system can be either "workspace sharing" or "workspace and time-sharing", depending on their function [12]. In both, each can perform tasks alone or together, so the worker in this type of cell acts as supervisor, operator, teammate, mechanic/programmer, and bystander [13]. This type of system is also defined by the level of interaction, where the robot and the employee can have the same workspace and task, only shared task and workspace or even a common task but different workspace.

2.2.1 Robots in the world

World's robots number has increased during the last few years and is expected to keep growing over the following years. The Figure 2.2 shows the actual numbers and expectations. Today is calculated around 3 million robots in the world.

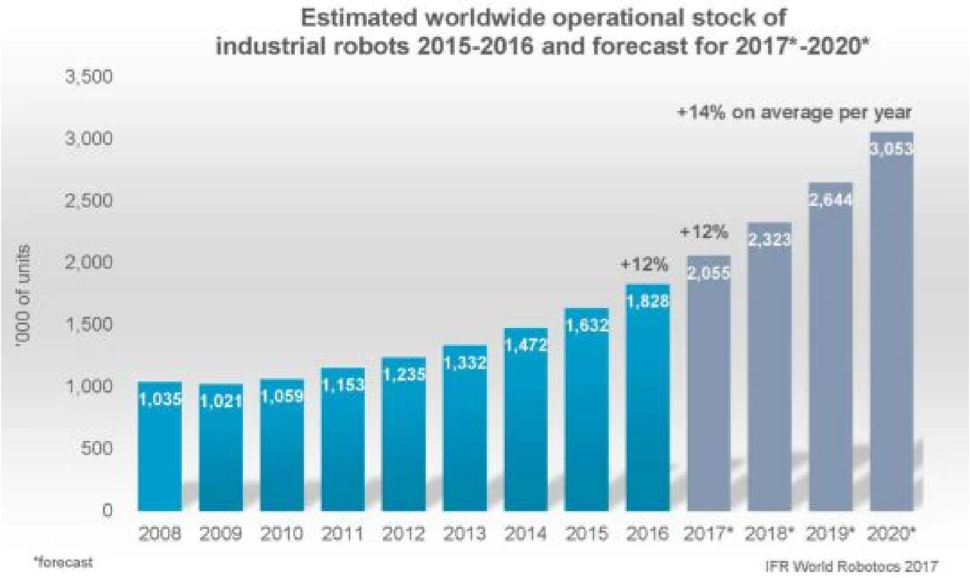
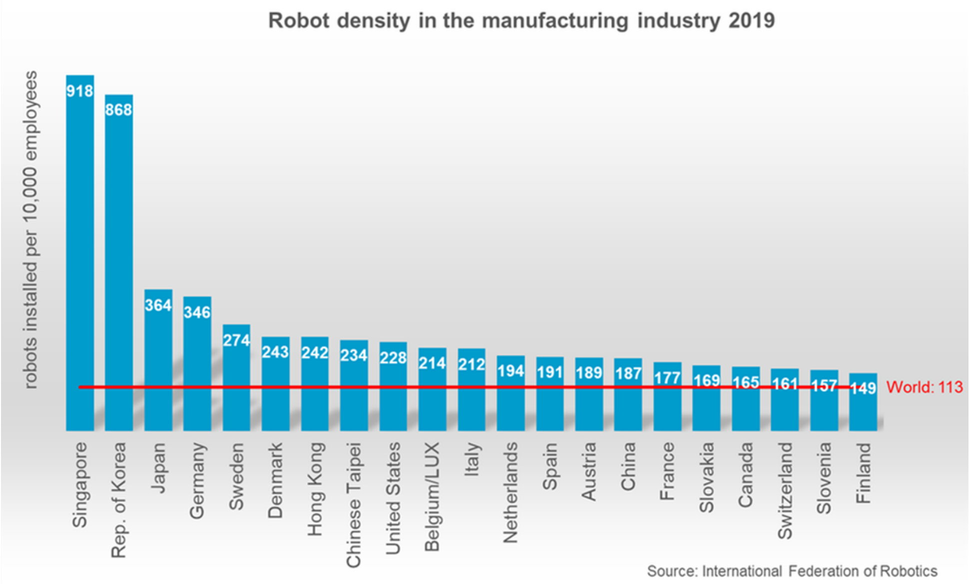


Figure 2.2: Number of robots in the world and growth predictions [14].

As seen in the Figure 2.2, robots are getting more common in industries, and it is expected to continue to grow. Nevertheless, these robots are not placed equally in each country. In Figure 2.3 it is demonstrated the top 20 countries with more robots per 10,000 employees.

The countries with more robots per 10,000 employees are Singapore and the Republic of Korea. However, the others are not there by coincidence. Singapore and China (also Chinese Taipei and Hong Kong) are very industrial countries, but there is a relation in why the others are placed there. Figure 2.4 shows the top 20 highest minimum wages in the world [16] to understand this link.



Source: International Federation of Robotics

Figure 2.3: Robot density per 10,000 employees (2019) [15].

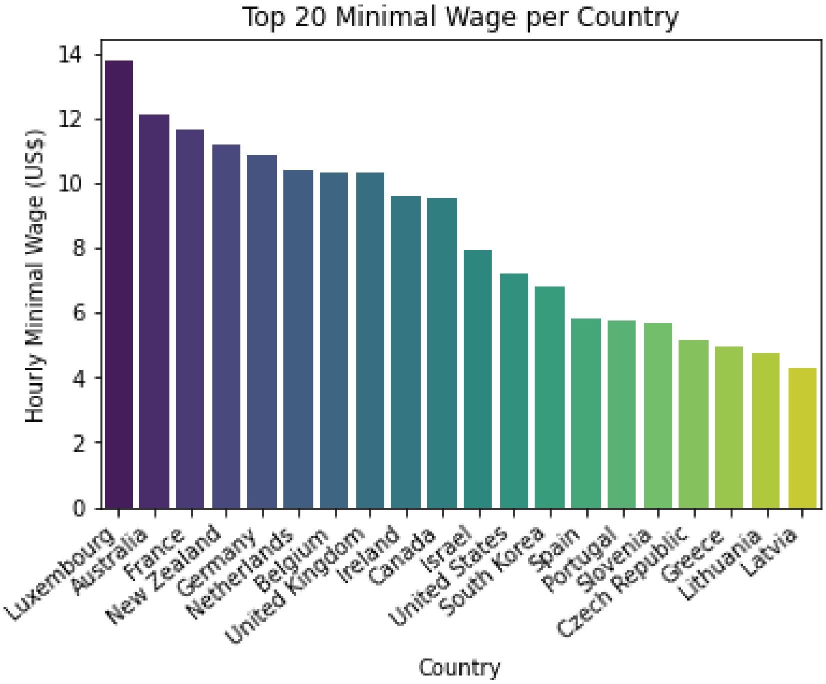


Figure 2.4: Top 20 minimal wage per country in 2021.

So, despite the four countries already cited, from the other 16 countries, ten are placed in this top 20 - disregarding Japan, that was not available in this study, but related to other years the country would be in this list. With this, it is possible to relate that countries where the wages are higher tend to have more robots in industry, because it is more beneficial and the price compared to an employee is smaller. That is, the number of salaries to reach the cost is lower.

2.3 Manipulator robots

The composition of an industrial robot is made by a robot manipulator, power supply, and controllers. A manipulator robot, seen in Figure 2.5, is a mechanism composed of multiple segments controlled to perform tasks in the environment. It is inspired in the human arm, and usually, the end-effector may be inspired in the human hand, i.e., a simple two-finger gripper [17].

Figure 2.5: Example of manipulator robot [18].

This robot is characterized by combining the kinematic structure, axis drive mechanism design, and real-time motion control, related to features as reach and dexterity, payload, quickness, and precision. To verify the performance is usually used testing, simulations, and other analysis techniques.

Reach is the maximum range that the robot can extend in the workspace, and, similarly, the dexterity is related to the angulation made by the joints in the movements. These features can lead to unusable spaces in the plant due to the inability to get there. Payload is another significant configuration that represents how much weight the robot can handle and should be respected to make the robot more durable and avoid accidents.

Quickness is not exactly the maximum speed of the robot. But the average speed in a working cycle. Due to this, it is not easy to find this metric in the robot specifications, also because it will also depend on the movements made in the cycle.

The effectiveness of an industrial robot is measured by different metrology or measurable characteristics. The most crucial measurable characteristics are repeatability and accuracy. The first might be defined as the ability to reach the same position over the tasks and reach the same point repetitively. Otherwise, accuracy is the distance between the achieved task and the requested task (i.e., the error). In other words, the first characteristic is to perform the same task frequently while the other is to hit the target each time. In Figure 2.6 it can compare the different cases of each.

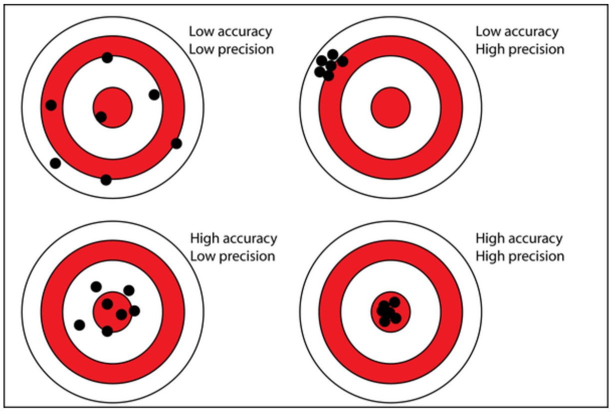


Figure 2.6: Differences of high and low accuracy and precision [19].

To perform tasks along a specific path, the robot needs to achieve the requested positions and orientations. For this, it demands to move precisely to desired points; otherwise, it can hit or not place the pieces correctly. The robot, as seen in Figure 2.6, can have four different situations according to its characteristics. It can reach the desired position several times, which is the best solution, with good repeatability and good accuracy. On the other hand, it can have only one of the metrics good, i.e., reach the same point but far from the desired or stay near to the target but with a difference between each time. The worst case is having a wrong approach for both, so the robot would not be near to target either be at the same pose at different times.

In a geometrical explaining, seen in Figure 2.7, the accuracy is the distance between the desired position and the mean position of all the achieved poses. At the same time, repeatability is defined as the smallest radius of the sphere that can fit all the points for the same requested task.

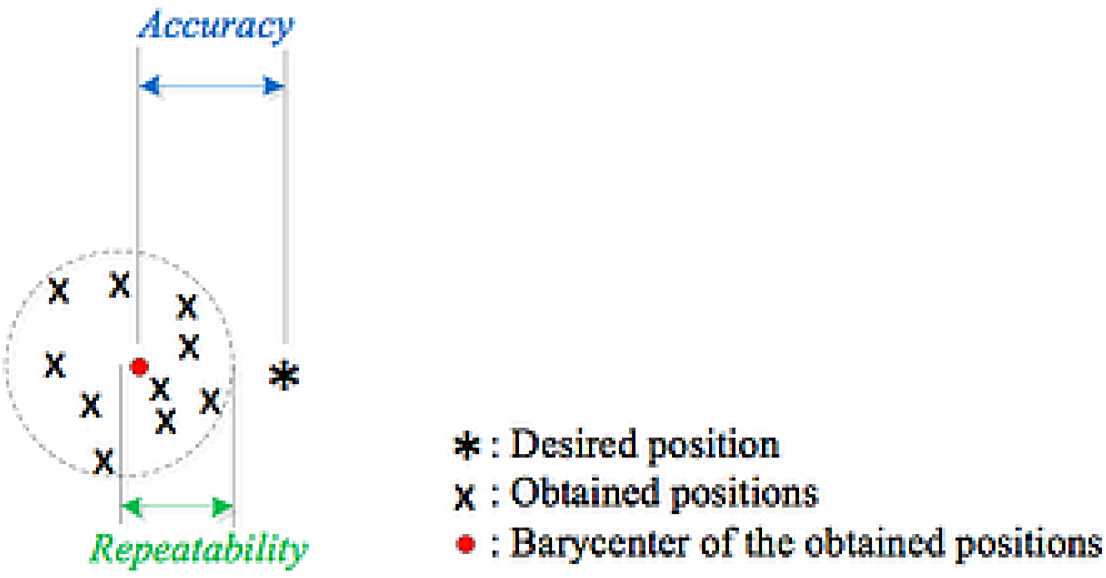


Figure 2.7: Geometrically approach for accuracy and repeatability [20].

The robots only have the repeatability feature, so a good manipulator is able to reach the same position several times. The metrics are defined by the ISO 9283 [21]. They also can be classified by the motion characteristics (planar, spherical, and spatial) or by the kinematic structure (serial robot, parallel or hybrid) [22].

They were initially used with radioactive materials but now are used in welding, pick and place, assembling lines, surgery, space. Usually, areas that are better for the operator to avoid physical contact. It helps handle too heavy and too hot articles, reduce human errors, decrease manufacturing costs and time, and avoid workers' diseases.

2.4 Collaborative robots

The robots have been upgraded during the last years. Today there are two main classes of industrial robots: the standard industrial robots and the collaborative robots (cobots). The second is one of the leading technologies of Industry 4.0, that like the usual industrial robots, can enhance production, ergonomics, and safety. With its ability to work alongside humans, the automation of new processes can use the best of robots and humans. They made changes in the idea of how humans and robots can share space, because this type of robot combines the efficiency of the robots with the possibility of working along with them because of the several numbers of sensors that make them safe for humans. Nevertheless, this is a new approach for robots in factories because initially, the industrial robots were designed to be robust, powerful, and enduring to do heavy tasks, so their path was not a safe place to be.

Despite safety, cobots can quickly redeploy a task, program, set-up inside the plant when the company does not want to make several changes in the layout, allow humans inside the cell, low initial cost, fast payback, and a quick unboxing and setup. In counterpoint, the traditional industrial robots are recommended on very high-volume and high-speed production, payloads over 16 kg or reach longer than 1300 mm. However, both types are used to integrate with other machines and robots, run without any employee, and automate processes that will not change over time.

Figures 2.8 and 2.9 compares the worksation of a cobot and an industrial robot.

In Figure 2.8 the cobot is working with an employee, while in Figure 2.9 the industrial robot has the cage to isolate it. This point is the main difference between both because the first allows humans to work alongside instead of replacing them. The co-work between cobots and humans can be seen as an assistant to the employees in dangerous, strenuous, or tedious tasks, creating a more efficient and safer workplace without eliminating factory jobs. By contrast, the industrial robots entirely replace the human, without any human

Figure 2.8: Collaborative robot working alongside human [23].

Figure 2.9: Industrial robot with cage [24].

help on the manufacturing floor [25].

Another distinction between the two types of robots is that the cobots are more easily to program [26] because their code can be changed by moving the robot to the desired position. In another way, industrial robots require more advanced programming knowledge to write a new code for any change in the process.

On the other hand, due to their size and working close to humans, the cobots are not designed for too heavy manufacturing - i.e., the strongest UR cobot (UR-16e) has a payload of 16 kg. Industrial robots can work with heavier objects but need a cage around them, while cobots are safer and do not require it [23].

According to the main difference between both, a recurrent theme is safety. There is a specified very low level of risk that is acceptable to exist while the robot works alongside an employee, defined by the severity and probability of an injury to the worker. To be considered collaborative, the robot cell must attend to certain levels of safety.

Safety is defined by a standard, which is a guideline determined by non-governmental organizations. The International Organization for Standarization (ISO) is responsible for managing a massive quantity of norms, including robot safety. An ISO standard is built in a way that the top-level standard is the first reference. As the level is decreasing, it gets more specific safety standards - in this case, to robots [27].

When it comes to robots, the top-level standard is the ISO 12100 - Safety of machinery, that refers to risk for all type of machines. The next level is the ISO 10218 - Robots and robotic devices, developed for robotic uses, detailing safety requirements for industrial and collaborative robots, being this difference specified during the last ISO update [28]. The cobots' safety includes, besides the robot, its end effector (i.e., the tool attached). The ISO 15066 is used to make any robot collaborative, but only cobots were designed to work alongside an employee [29].

According to Cobot Intelligence Inc. - a Techman Robots distributor - the worldwide revenue of Collaborative Robots was, in 2017, about 306.3 million euros, and this number is predicted to reach 8,013.6 million euros in 2025. Of this market, the automotive industry is responsible for a 20% share in the market. A Chicago-based firm, Loup Venture, expects cobot shipments to increase from 8,950 units in 2016 to around 434,404 by 2025, representing a market value of around 7,4 billion euros. In Figure 2.10 is possible to this growing during the last 3 years [30].

The key suppliers in this market are ABB, Fanuc, KUKA, Rethink Robotics, Universal

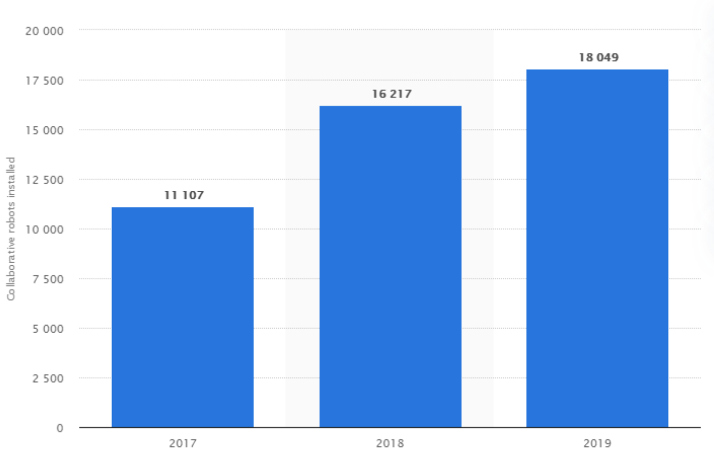


Figure 2.10: Number of cobots in the world.

Robots, and Yaskawa Motoman. Moreover, the models can be available at prices as low as around 24,500 euros. Also, this robot type has, according to Universal Robots, a Return Of Investment (ROI) of 6 months.

2.5 Robotic simulation

To find a solution for the implementation of robots, a common approach is to first simulate the environment before acquiring the robot to test and verify the best solution and ideas.

A definition for simulation, according to [31], refers to the complete process of problem synthesis, model formulation, optimization, computer implementation, validation, experimental design, and analysis presentation of the results.

The use of simulations started to increase thanks to aviation training which has an experience of over half a century, and "lessons learned" with simulators and simulation [32]. These simulators are used to improve psycho-motor tasks or increase team performance, reducing accidents caused by human failures. With this, the aviation field recognizes the benefits of using simulators by the results of almost eliminate accidents on air traffic.

2.5.1 Characteristics of simulation

Simulation is a very effective way to learn [33] by testing and modifying rules, try different inputs, and check the outputs. The possibility of using this resource allows us even to predict the behavior of a particular object, sensor even if it does not exist. It can check the results of a system before the implementation, making it a handy feature in developments, by solving "what-if" questions, i.e., if it is better to place more sensors, more robots or if it will increase production and other questions that help to evaluate the system.

Also, simulation has other benefits: it can save money because the developer can test if each accessory is needed, which is needed, the correct size, so avoids buying the unnecessary or wrong equipment. Furthermore, there is still the benefit of seeing whats is really happening in the environment, like when presenting a proposal to a person outside the research area, the simulation provides visual feedback, so the client does not need to know what is exactly happening in the back-end, he is able only to see the environment working. So the client can decide to buy or not by seeing the system working and understanding it visually, with results of expected process and productions instead of investing in a risky solution.

Despite the use in aviation, the use of simulation has grown to research areas and also for education and training [34]. It has happened due to a decrease in computing power costs, making it economically viable. According to [32], the importance and reason of this growth are:

- Is applicable to students of all levels and ages.
- Helps to see and work with expensive and dangerous environments.
- Allows teaching subjects in practice.
- Provides new methods of problem solving.
- Provides realistic training.
- Is cost effective without risks to humans.

A simulation is an essential tool in robotics. This is because it allows the study of the structure, characteristics, and pose of the robots in different levels, increasing the simulation role as the system complexity increases. With this, exists a large amount of simulation software for robots that usually focus on the motion of the robotic manipulator in different environments [33], like the trajectory and kinematics. Among the available software, it is essential to mention the ABB RobotStudio, RoboDK, V-Rep, and Gazebo, being the last two with built-in support for ROS (Robot Operation System).

Although, the disadvantages of simulations are that mistakes may be made in the model's rules, providing results not so reals. The computational costs of running many simulations may be high and slow, and some may need a significant amount of time for the results to make sense. Despite this, sensors may respond differently in the simulator, and cameras' frames do not have light interference. Another point is that some people may not feel comfortable or trust the results showed.

The simulations are necessary when developing automated systems or robotic workcells. A robotic workcell simulation is "a modeling-based problem-solving approach that aims to sufficiently produce credible solutions for robotic system design" [35]. They are essential and necessary to get the exact knowledge for material and operations with the robots and their peripheral devices. The deployment requires successful applications of concepts, tools, and methods for the product design and the plant control support [36]. For this, the simulation is used to achieve this goal.

The design of robotics solutions can be improved through the use of simulation [37]–[39]. The first is to eliminate guessing, unrealistic expectations. Also, the optimum solution can be found by evaluating different alternatives. The second is that changes in the design are much more manageable and fast when compared to the real plant. Finally, it brings a safe environment for tests, optimizing, and finding the best solution.

Models in simulations are principles to study the actual workcell over time. The models can be geometric objects, mathematical equations and relations, or graphical representations [40].

Robotic simulation software is often used, and the process often involves inductive and deductive reasoning and requires multifaceted knowledge in diverse disciplines such as Computer-Aided Design (CAD), machine design, and robotics [35].

Chapter 3

Description of the case study

Catraport is a company located in Bragança that belongs to the group P&C Automotive. This factory produces metal components for the automotive industries and was born to attend to the growing demands of two of the group's largest customers. Due to this, this company always has a goal to increase their production, and they had a machine that was not producing the desired quantity of pieces.

3.1 Original layout

This process initially considers the two machines located in two different spaces, so the employees must do the tasks in the first machine for a time. Then they would have accumulated several pieces for further move those pieces to the next station (i.e., calibration). With a significant quantity of pieces, the employee would stay in front of this machine, placing the piece inside the machine and lately palletizing it. This waiting time to have a certain quantity of pieces ready for the second machine was a lost time because they must wait this whole time for only then move to the next. The starter production was of over 1600 pieces per shift.

The case study station comprises two machines: a cutting machine and a calibration machine. The first machine is the Omera R400, illustrated in Figure 3.1, that is responsible for cutting the pieces. This machine has a total cycle time of 17.08 seconds, divided into two stages: the cutting time and the movement time. The cutting time comprises when the machine is busy processing the piece and takes 10 seconds to finish. Also, the movement time is when the piece is already finished and moves to the end of the machine that takes 7.08 seconds. The piece is ready to be moved to the next machine at this stage, and another one can be placed in the machine.

Figure 3.1: Omera machine for cutting metallic pieces.

The second machine, illustrated in Figure 3.2, has a cycle time of 1 second. It operation work is the following: the piece in placed in the machine, a press button is pressed, the machine calibrates the piece and finally the piece is removed from the machine and it is palletized.

The pieces arrive to the station in a pallet in a totally random way, sometimes placed one inside the other, sometimes with the face down. Figure 3.3 and Figure 3.4 show, respectively, how the pieces arrive to the station to be processed and how they should be placed at the end of the process.

As seen in Figure 3.3, the pieces are not organized, what makes it not a simple task for recognize and identify the correct position for picking the piece and star the process.

Figure 3.2: Calibration machine.

Figure 3.3: Parts arrived to the station.

Figure 3.4: Parts departure from the station.

And, in the Figure 3.4 it is able to notice the organized way for the output box, so the pieces should not be left in a random way inside it.

The piece produced in this machine is better seen in Figures 3.5, 3.6 and 3.7. It has a diameter of 154.6 mm, a minimum height of 22 mm and a maximum height of 50 mm.

It also has two holes: a circular hole with 27.2 mm of diameter and an elliptical hole that has 64.8 mm in the major axis and 38.6 mm in the minor axis.

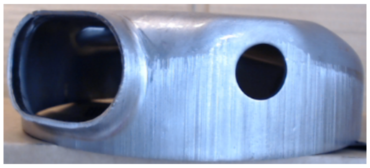


Figure 3.5: Front of the piece.

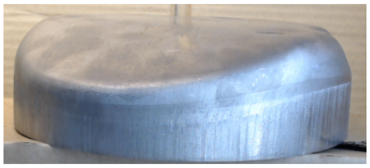


Figure 3.6: Back of the piece.

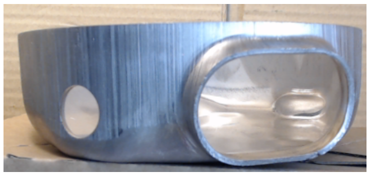


Figure 3.7: Piece with the concavity up.

Another point to consider in the model of the piece is that the borders are sharp, so the employees must be careful when manipulating them to avoid any accident.

3.2 Actual layout

After the first studies the two machines were placed in the same location, being now adjacent inside the station.

As previously referred, the machines were placed in two different spots of the factory plant. Considering that this distance could cause a loss of time, it was suggested, at the beginning of this study, to the company to re-organize them in order to the second stays close to the end of the first, so it would be able to do the process sequentially, without wasting too much time. So, the new area for the machines in the factory is shown in Figure 3.8.

Figure 3.8: New layout for the machines.

In this space, the machines would be positioned as the Figure 3.9.

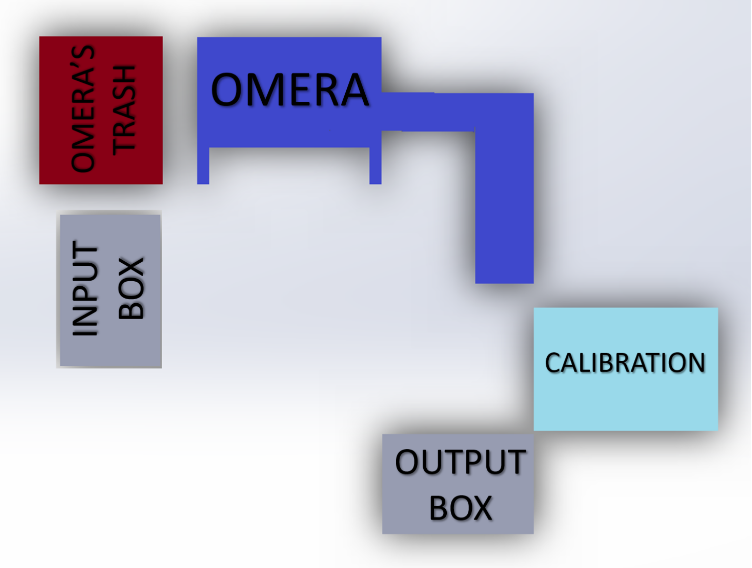


Figure 3.9: How the machines are placed in the new layout.

In this picture, the darker blue is the Omera machine, the light blue is the calibration machine and the grey boxes are the pieces' boxes, being the left one where they arrive and the right one the final stage.

With this new layout, the production flow worked as seen in Figure 3.10.

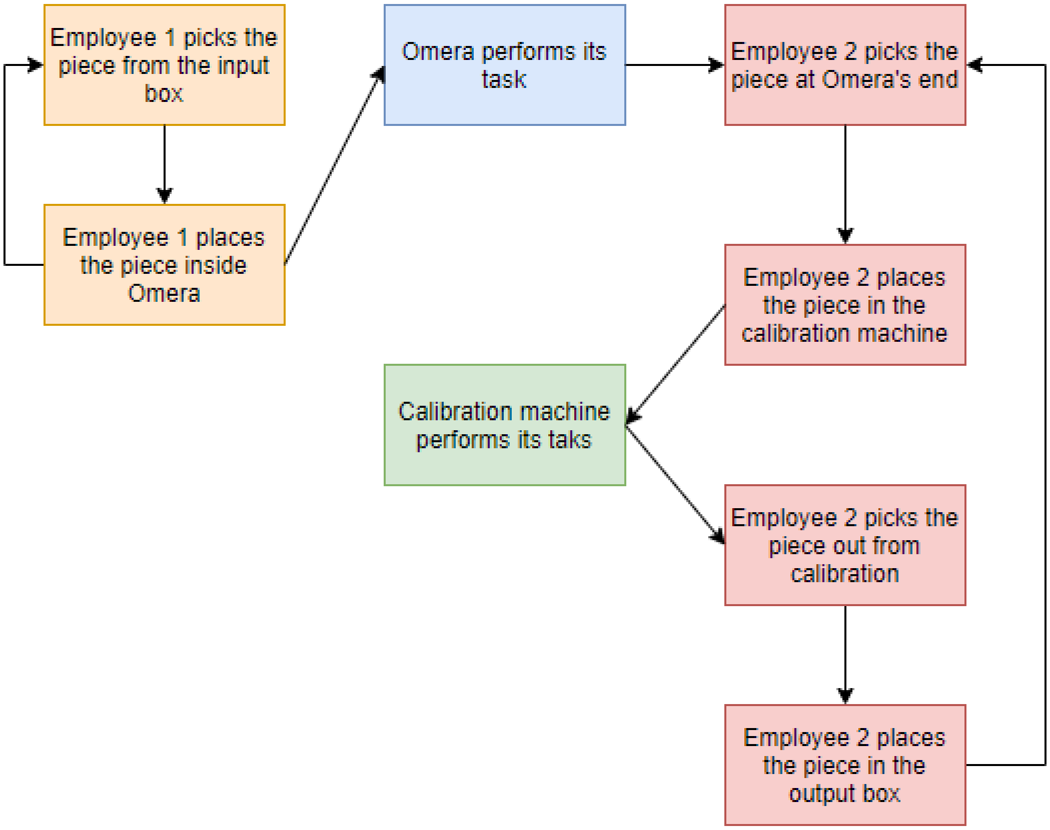


Figure 3.10: Production flowchart according to the actual layout.

In this new layout the production now works in a sequential mode, so, when the piece is done in the first machine it is already able for the employee to perform the next task, by placing it inside the calibration machine and then in the output box.

There are some aspects in this process that should be also taken into consideration during the study. The first is the way that the pieces arrive, randomly placed in the pallet. The second is that the machines have an exact way to place the pieces inside. Also, the pieces reach the end of the Omera machine with the face up and must be placed with the face down in the calibration machine. Another point is that the calibration machine does not have a wide space for inserting the pieces.

3.3 Development of automated solution

For this case of study, the idea of automate the process was the solution that could attend to the company's requirements. So, for this, would be installed one or more robots that would do the tasks and increase the production. To decide what is the best solution, the following chapters describe the simulation methods used to understand which was the best result in terms of production and also in cost-benefit.

The simulation will be used to try different possibilities, different approaches to perform the tasks described in the flowchart of Figure 3.10. With a goal to the machines produce more pieces in less time, the objective of this work is to develop the best solution and further provide the requirements for the cell, enabling the company to purchase the equipment, and lastly proceed with the installation process, to make the system work properly like the simulations.

To develop the simulations is needed to study each process, what are the bottlenecks of the system, the method of picking and placing the piece at each station, and also in the output box.

Chapter 4

Simulation of the robotic solution

This chapter presents the three studied options to automatize the transfer system inside the station using robotics, considering the previously referred requirements, which and why was the selected option, and the following procedure to the installation.

4.1 Study of alternative robotic options

Each one of these options was modeled and simulated using robotics simulation software. The software used was ABB RobotStudio, because it was the software available at the university.

The simulations are composed of two stages: the first at the beginning of Omera and the second at the end of it and close to the calibration machine. The first stage is where the pieces are taken from the box and inserted inside Omera. The second is where the pieces arrive at the end of Omera, are inserted in the calibration machine, and then placed organized in the box. For the second stage, since for the calibration, the pieces are inserted horizontally, and they should be picked from the top in the pallet, an intermediate station was inserted, in the simulation, a parallelepiped of 250x250x900 mm, where the robot would use it as a support for changing the contact area with the piece.

4.1.1 Option 1: one robot

The first option considers using one robot to perform all the tasks inside the station, namely being responsible for inserting the piece in the first machine, taking it off and inserting it in the second machine, and finally palletizing it. For this purpose, as illustrated in Figures 4.1 and 4.2, the robot uses a rail to move between machines.

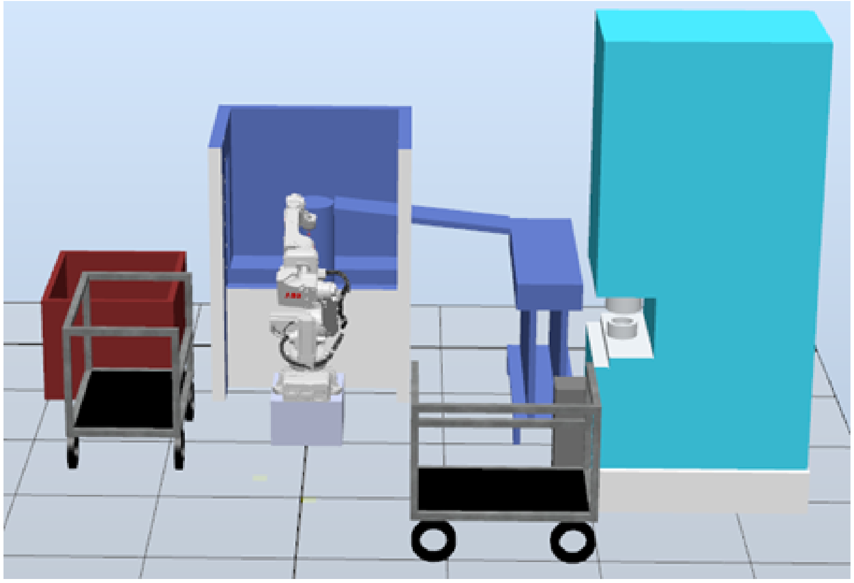


Figure 4.1: Simulation model for the first option.

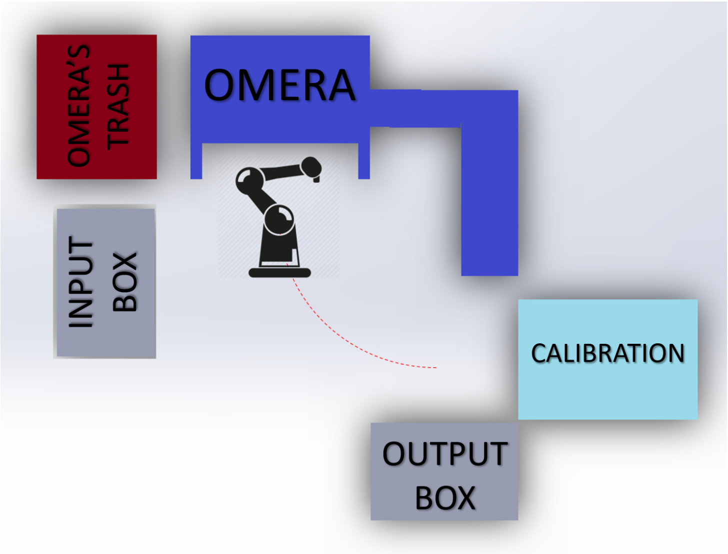


Figure 4.2: Upper view for the first option.

The operating process of the transfer system using only one robot is represented in the flowchart illustrated in Figure 4.3.

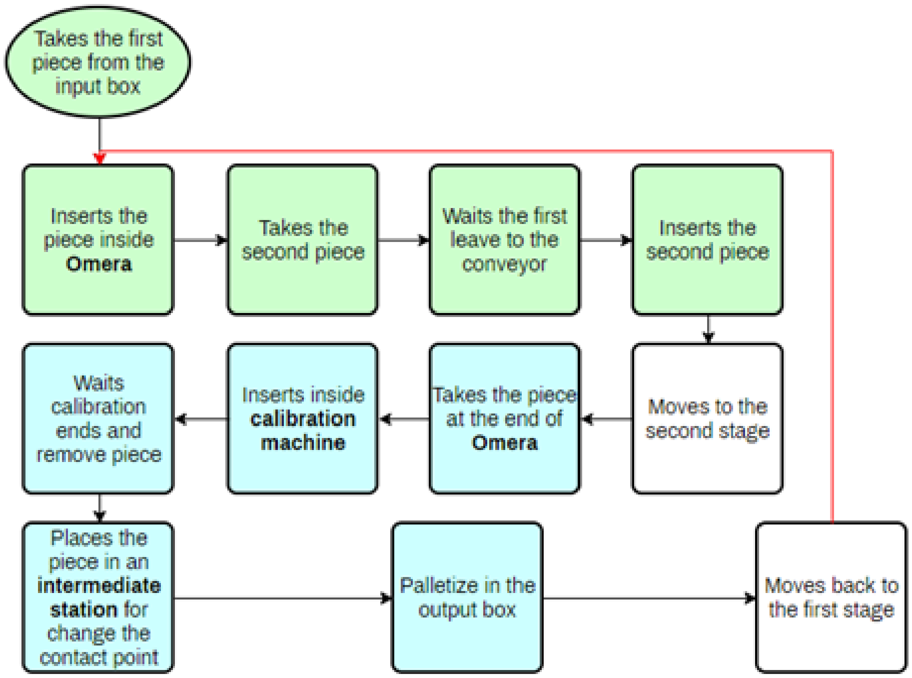


Figure 4.3: Flowchart of the transfer process for the first option.

The green elements represent the actions at the first stage while the blue are related to the second stage, while the white elements are the transitions between both stages.

After simulated the designed model, the achieved results show that the robot takes 3.4 seconds for pick and place the piece in the first stage, 3 seconds for moving from one stage to the other, and 9.5 seconds for performing the tasks at the second stage. So, the cycle time of this process, i.e. between the robot takes one piece in the beginning box and its following piece, 21.8 seconds elapsed.

Considering that between a piece is inserted in Omera and reaches its end takes 17.08 seconds, using this option, 4.72 seconds were lost due to the robot cycle and movement. Note that, as indicative, the movement of the robot was based on the ABB rail IRBT 2005, that is able to move at a maximum of 2 m/s, but, considering the weight of the robot, was used a speed of 1 m/s in this simulation for avoid overcharging.

In addition to the cycle time problems, this option takes the problem of having to install a rail to support the movement of the robot between the two stations and the way to automatize the picking of the pieces that arrive at the beginning of the process (actually organized randomly in the pallet).

4.1.2 Option 2: two robots

The second option considers two robots to perform the transfer process, the first one to pick and place pieces in the Omera machine and another to take the pieces from the first machine, insert in the calibration machine and finally to palletize them, as illustrated in Figures 4.4 and 4.5.

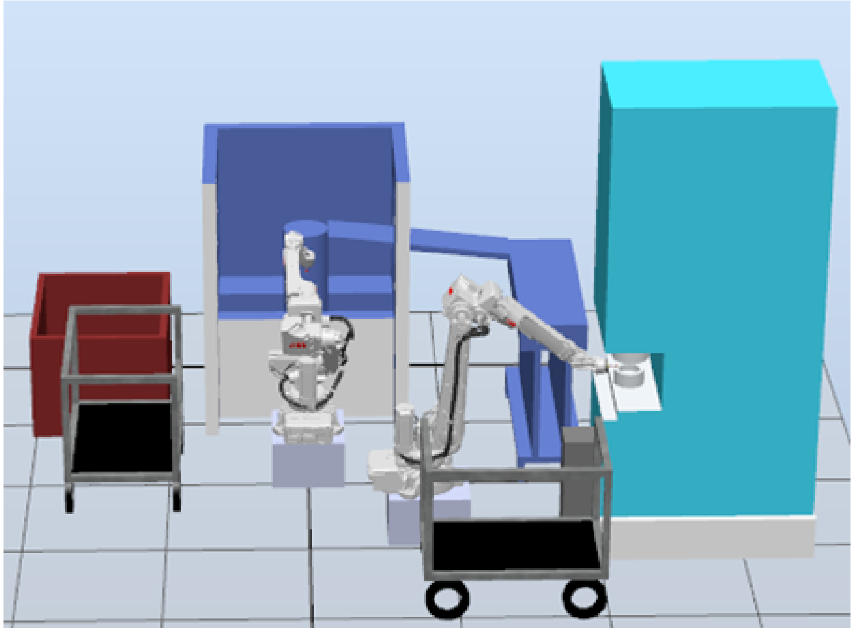


Figure 4.4: Simulation model for the second option.

The operating process of the transfer system using two robots is represented in the flowchart illustrated in Figure 4.6.

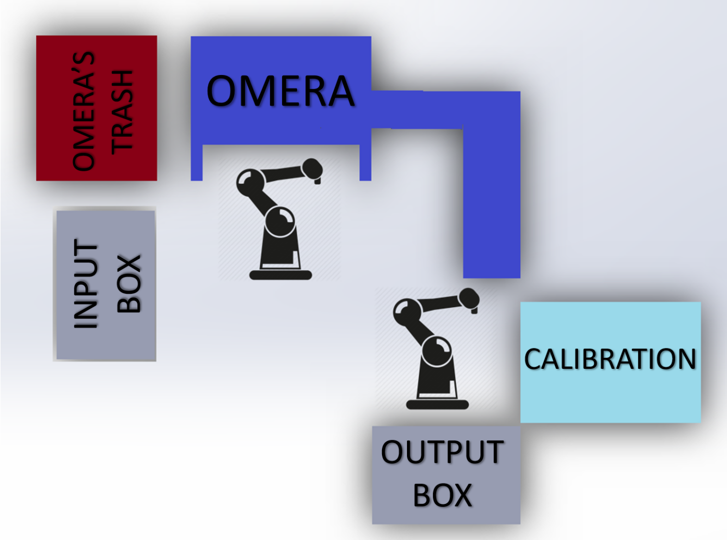


Figure 4.5: Upper view for the second option.

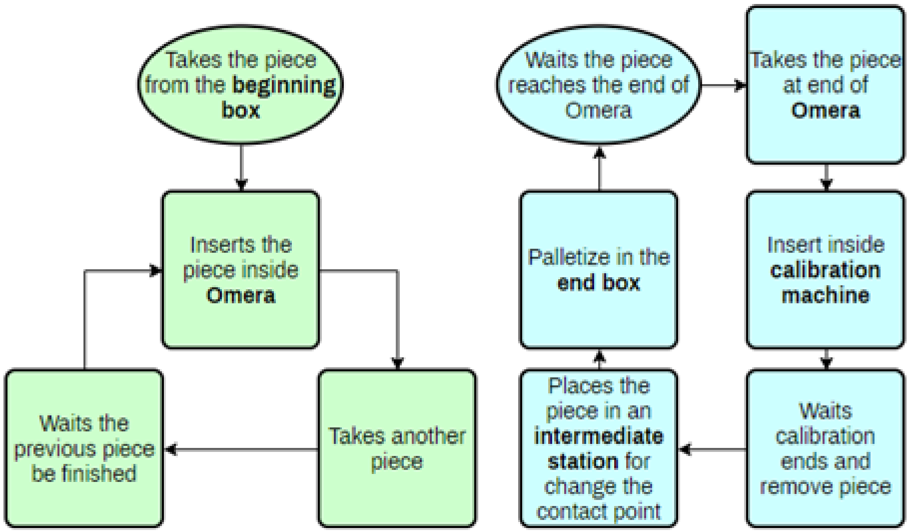


Figure 4.6: Flowchart of the transfer process for the second option.

The green and blue boxes represent the same as the last flowchart. But, in this case each robot is responsible for one station. So, one robot will only do the tasks at first stage (green elements) while the other will work only in the other (blue elements).

The cycle time for the first robot is 11.9 seconds, considering that it remains 6.4 seconds stopped and waiting the piece leaves. Also, for the second robot, the cycle time is 9.5 seconds, while the pieces arrive at the end of Omera machine every 11.7 seconds, making the robot able do its whole routine before another piece is done.

This option presents good results in terms of productivity but it requires a strong investment in the acquisition of the two robots. Additionally, it requires the need to automatize the picking of the pieces that arrive at the beginning of the process (actually organized randomly in the pallet).

4.1.3 Option 3: a robot and a operator

This option is a hybrid approach that combines the best of previous options aiming to be faster and cheaper. For this purpose, it considers a robot and an operator, as illustrated in Figures 4.7 and 4.8. The operator is placed in the first stage, pick and place the pieces in the Omera machine, and the robotic arm is responsible to pick the pieces at the end of the Omera machine and place in the calibration station and finally palletize them.

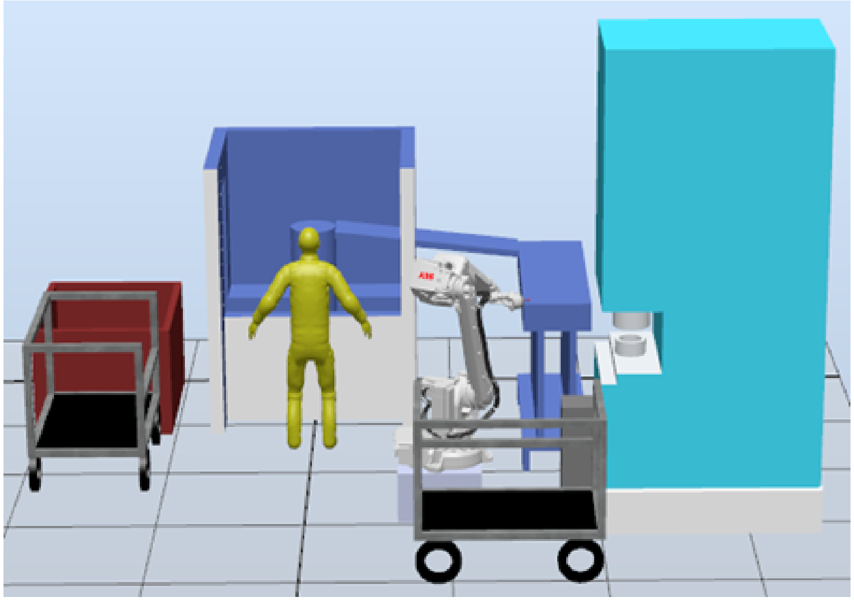


Figure 4.7: Simulation model for the third option.

The operating process of the transfer system using one operator and a robotic arm is represented in the flowchart illustrated in Figure 4.9.

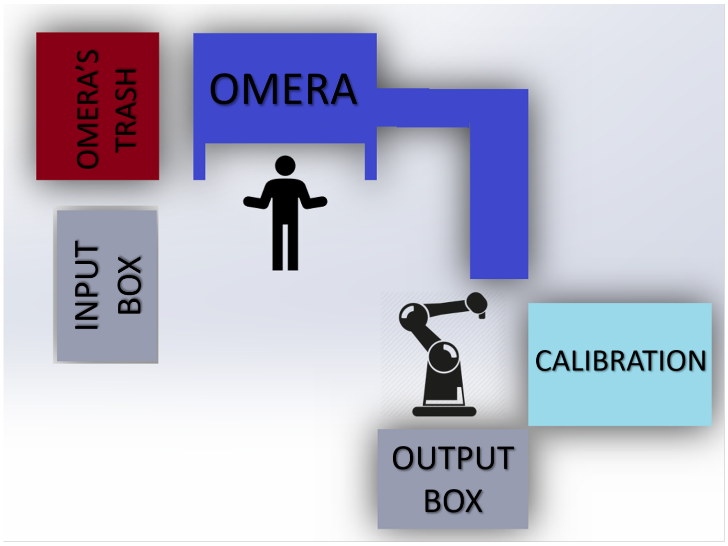


Figure 4.8: Upper view for the third option.

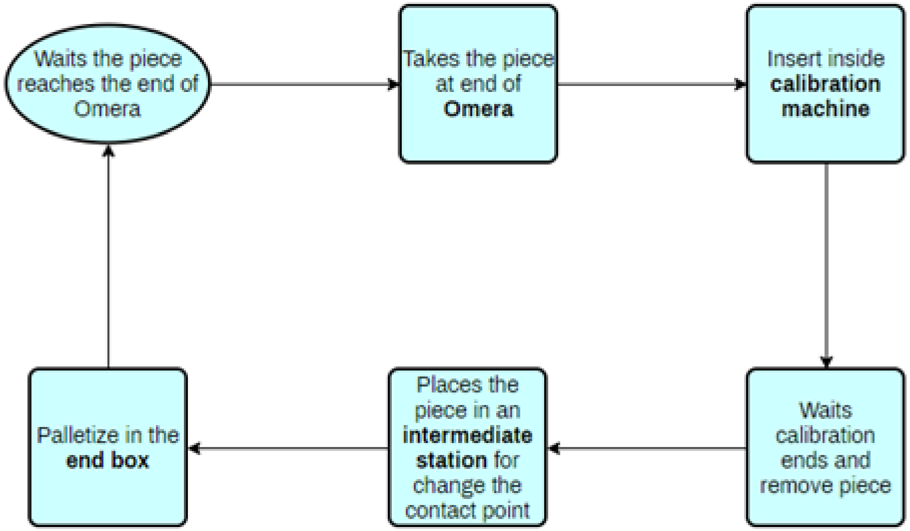


Figure 4.9: Flowchart of the transfer process for the third option.

As it can be noticed, the robot works only in the second stage and has a cycle time of 10.9 seconds, while the pieces reach the end of the Omera machine almost every 13.3 seconds – this time is the cutting time plus the time for place another piece inside the machine plus the time for the Omera machine be free. So, the robot finishes its routine before another piece is done.

For the simulation effects, it was set a value of 1 second for the time that the employee takes to place another piece inside the Omera machine, after the previous has already left for the conveyor. This time is the same that the robot takes in the second layout, that consists in just placing the next piece, so, while the piece is being processed, the employee could already pick the next one.

This option presents good results in terms of productivity and only requires the investment in one robot. Additionally, it does not require the need to automatize the picking of the pieces that arrive at the beginning of the process (actually organized randomly in the pallet).

4.1.4 Comparative results

The performed simulation of the three different alternative solutions allowed to extract operating production parameters that are summarized in Table 4.1.

Option	Pieces/minute	Time for 1 piece (s)	Pieces in 7 hours
1	2.76	21.73	1159
2	5.10	11.66	2161
3	5.10	11.70	2153

Table 4.1: Comparison of results and times for the three simulations.

As seen in the table, the second and third options are the ones that presents more productivity.

In fact, the first option requires one robot, a rail for it movement from one station to the other and an automation system for picking the pieces from the initial pallet. This movement of the robotic arm implies a slower operation, making this solution the less productive (takes approximately 2 times more for produce each piece), resulting in 46% less productivity.

For the second option, there are two robots that need to be acquired and the process to automate the picking of pieces from the initial pallet. This solution, as well as the third one, reaches the fastest and more productive environment, but it requires the acquisition of two robots, which makes this solution at least 2 times more expensive than the others.

The third option requires only one robot and no need to automate the picking of pieces from the initial pallet. Considering the results, it has a best cost-benefit relation, because it has approximately the same results as the second one (a difference of 1.25% in production), but it does not need the investment to automate the picking of pieces from the initial pallet, what saves money.

4.2 Simulation's final considerations

According to the achieved simulation results, the third solution (one robot and one operator) is the one that presents best cost-benefit relation. This solution enables to improve the production to a point that it is almost the fastest possible (considering that the robot does its routine before another piece arrives, so depending only by the gap between one piece leave and another is inserted) with the cheapest scenario, where there is only one robot and does not need to automate the picking of pieces from the initial pallet, which is needed for the two others. This automation requires an additional investment and a not trivial solution (the possible solutions can be hard to implement and could result in slowing the simulated times).

However, the adoption of this solution requires:

- The acquisition of a robotic arm to make the manipulation in the second stage of the process. The minimum requirements for this robotic system are:
  - Working area: For the machine 2, the distance between the further two points is 2380 mm, and considering that for the palletizing, the robot should be able to vary only the piece height, without moving it in other axis or orientations, so the robot should have a range of 1.8 meters for an industrial and 1.3 meters for a collaborative. For the machine 1, this distance is 2402 mm (considering the input pallet in the current position), what requires a robot with the same range as the last.

  - Payload: 1 kilogram, but for robots with the specified range they already have a payload for 8 kg (e.g., the ABB IRB 2600ID-8/2.00).

- Since the factory plant has always operators moving inside the factory, the robotic arm to be considered be a collaborative robot. That kind of robot allows people to work together, because the robotic arm is equipped sensors that would stop or reduce the speed of the robot when the operator is nearby. This allows robots to continue their work without to stop their routines while replacing the input and output pallets.

- A safety system, e.g., using a radar system, should be implemented in order to guarantee that in certain situations that robot will stop its movement in presence of non-authorized persons. Note that the a planar sensor is not able to distinguish between a person and an object, even between an authorized and non-authorized. There are some models of radar sensors (i.e., SBV-01) that are able to perform this task.

- The acquisition of a robotic gripper to grab the pieces, that can be a vacuum or magnet gripper. The vacuum gripper provides a better handling for non-flat surfaces, that is the case for the actual pieces, allowing to handle pieces from different angles, without losing the grip (however requiring always that the occurrence of vacuum conditions are ensured).

- The implementation of some changes in the calibration machine (for all options considered) and in the Omera machine (for the two first options). Those changes are related to automate the process, e.g., allowing that the machines would start their routine automatically when the pieces are placed. This process consists, e.g., in replacing the start buttons for a logical signal that the robot would send to the machine when the pieces are already placed.

- The automation of the picking of pieces from the initial pallet, allowing the robot to pick the pieces in the correct way. Some possibilities:

  - Insert a vibration system in the pallet, with a one way out according to the piece's size, in order to make the pieces leave one by one the pallet, through a groove. The size of the pieces may constitute problem to this solution, as well as this would not flip the piece to a correct orientation.
  - Insert a conveyor for the pieces reach a point where the robot would pick them. This solution implies the use of an operator to place the pieces in this conveyor, which could be contradictory to the adopted solution that aims to remove the operator from the station.
  - Guarantee that the pallets are coming properly organized in the pallet, which combined with the use of a camera installed in the robot will allow to recognize the exact orientation of each piece so would set a possibility for the robot reaches the correct side of the piece.

- Consider the possibility to periodically exchange the position of the operator and the robotic arm, aiming to reduce the monotony of the tasks execution by the operator. This will require the implementation of a rail system to allow the robotic arm to move between the Omera machine and the calibration machine.

- Consider the possibility to move the input pallet to a higher place, decreasing the robot range at this stage.

After presenting the results to the company's director and all staff, they decided by choosing the third solution: the hybrid solution that uses one employee and one robot. As discussed, this solution has the best cost-benefit for having only one robot and no additional safety accessories.

With this, started the search and talks to the distributors to find the best option for the factory. Due to the facilities, no need for isolation or cage, the idea was to acquire a collaborative robot with the specified requirements.

4.3 Acquisition of the robot

Three robot developers have been contacted with the mentioned specifications: KUKA, ABB, and Universal Robots. The two firsts said that they did not have collaborative robots for that range, but they could install a collaborative system for the robot. This system is made by LIDAR sensors that would detect the proximity between a human and the robot, so when someone is getting closer to the robot, it will decrease the speed until it stops when too close. One problem is that it will not recognize if it was a person walking thru, a piece, a box, or something else near. With this, the system could work at a lower speed without having an employee nearby.

Another idea proposed by ABB's seller was to use AIRSKIN. It is a soft and pressure-sensitive safety skin for various types of robots and tools, making the robot stop when hitting or being touched by someone. It has a safe collision sensor for industrial robots that can turn the robot into collaborative. It would cost around 4000 euros to 5000 euros (price point for a UR10 - around 10 to 11 pieces, said by the owner) [41].

Nevertheless, as initially reported, the company's idea was to have a collaborative robot, due to its characteristic, referred to in Section 2.4. So, the talks with Universal Robots were intensified, being proposed the UR10 e-Series, with a wrist camera (Robotiq Wrist Camera) and an adaptive gripper (Robotiq Hand-e Adaptive Gripper). The UR10 e-Series is a collaborative robot, with a built-in force/torque sensor, with 17 safety functions (all EN ISO 13849-1, Cat.3, PL d, certified by TÜF NORD), full EN ISO 10218-1 compliance (certified by TÜV NORD) with intuitive programming flow and easily replaceable joints. It also has six freedom degrees, a payload of 10 kg, and a reach radius of 1300 mm.

Axis movement	Working range	Maximum speed
Base	± 360°	± 120°/s
Shoulder	± 360°	± 120°/s
Elbow	± 360°	± 180°/s
Wrist 1	± 360°	± 180°/s
Wrist 2	± 360°	± 180°/s
Wrist 3	± 360°	± 180°/s

Table 4.2: UR10 e-Series axis movement.

This robot works in a range of 0 to 50°C, has a repeatability of ± 0.05 mm, and the working range and maximum speed are specified by joints in Table 4.2.

As seen in Table 4.2, the robot has a joint freedom movement of 720° on every axis.

The adaptive gripper was a solution proposed because the piece has an irregular shape, and the calibration machine requires an exact way of feeding it and a small space for robot action. With this, the idea was to pick the piece on its front opening. Therefore, a finger was developed for the gripper that fits precisely inside the piece. For this finger, it was considered the opening angulation and shape. So the piece could be easily grabbed and would stay steady. The gripper is displayed in Figure 4.10.

The other accessory that was acquired along the robot was the wrist camera. It will be used to identify the piece and its orientation to the robot pick it regardless of its position at the end of the Omera machine. The camera is the one in Figure 4.11.

Figure 4.10: Robotiq Hand-e Adaptive Gripper.

Figure 4.11: Robotiq Wrist Camera.

Chapter 5

Robot installation

With the robot and all the accessories available, the installation started. First, it was necessary to make all the connections, place the accessories, configure and calibrate them and then program the robot routine.

5.1 Hardware installation

The first step was to fix the robot on its support, and, to help and accelerate the process, the employees already placed it. However, the gripper and camera were not installed, so to pass their cables were necessary to unscrew the robot, pass the cables, and screw again. The robot on the support is seen in Figure 5.1.

The camera and gripper installation were both composed of two steps: fix in the robot and further the software installation. With the robot turned off, the first to be fixed was the camera. It is fixed by placing it on the robot arm and aligning the dowel pin with the tool flange. Then, it was mounted using the provided screws and lock washers. The gripper was also mounted on the camera with the provided screws and lock washers - the Wrist Camera interfaces with an end-effector (e.g., a Robotiq adaptive gripper) via a 10-spring pin connector on its outer surface, does not need the direct connection between the gripper and the robot. Both fixed on the robot's arm are shown in Figure 5.2 and a closer view in Figure 5.6.

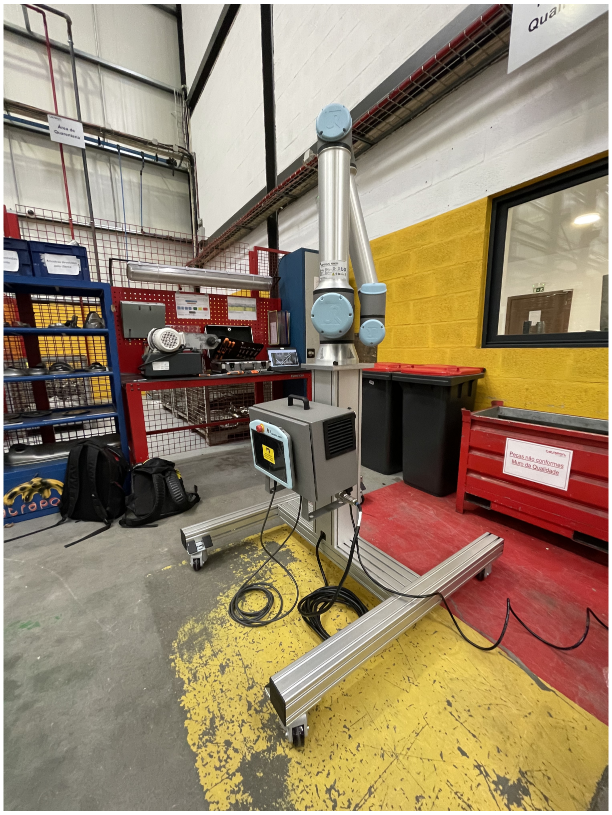


Figure 5.1: Robot placed on the support.

Lastly, the camera cable was attached along the robot arm using nylon clamps. The end of the cable has a USB port and power supplies. At the robot's controller, the red wire was connected to a 24V slot and the black to a 0V, like in Figure 5.4, and the USB attached to a four-port USB hub that was already supplied with the camera, the same as in Figure 5.5. In this hub was also connect a USB license dongle for the camera and a 32 GB pen drive, and the hub was further connected to the controller. In the pen drive were the camera and gripper software previously downloaded at Robotiq Support page, extracted, and moved to it.

In the gripper, the factory finger was replaced by a customized one. This was made by the seller and was designed to fit in the piece opening. The new finger is the showed in Figure 5.6.

At this time, the accessories are correctly fixed and ready to be installed. So the robot is connected to energy and turned on.

Figure 5.2: Gripper and camera placed on robot's arm.

5.2 Accessories configuration

The next step is to install each software. For the camera, it was necessary to navigate to the settings tab, "system", "URCaps", the "+" button and select the "Robotiq_Wrist _Camera-X.X.X.urcap" file and reboot the system. Then in the installation tab, "URCaps, "Camera", click in "Dashboard" to see the Vision System status. To check the installation is just back to the Camera tab, and the output image will display.

The installation was almost identical for the gripper, but the file was "Robotiq _Grippers-X.X.X.urcap". After restarting, it is already installed.

5.2.1 Accessories calibration

Now that both are placed and installed, it is needed to calibrate them. To calibrate the gripper, it is just to measure the space between the fingers when it is closed and open.

Figure 5.3: Gripper and camera placed on robot's arm.

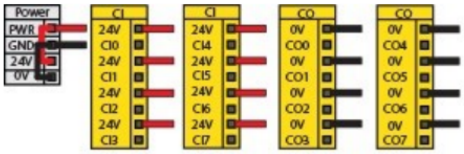


Figure 5.4: Power supply in the UR-10e [42].

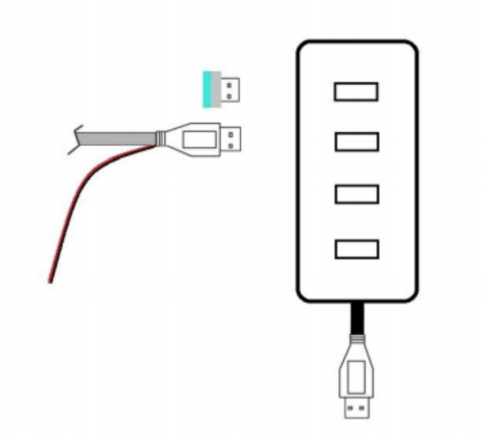


Figure 5.5: Connections to the USB hub [42].

With these measurements, in the installation tab>"URCaps">Gripper insert them, it will now display the distance that the gripper is opened and not only in percentage.

To calibrate the camera, the software already has a built-in function for it. So it is just to place the chessboard for calibration (Figure 5.7, align the camera, and start. The robot will center it to the frame and start making some movements to get different angles.

Figure 5.6: Developed fingers for the gripper.

After this, it will have a workplane calibration.

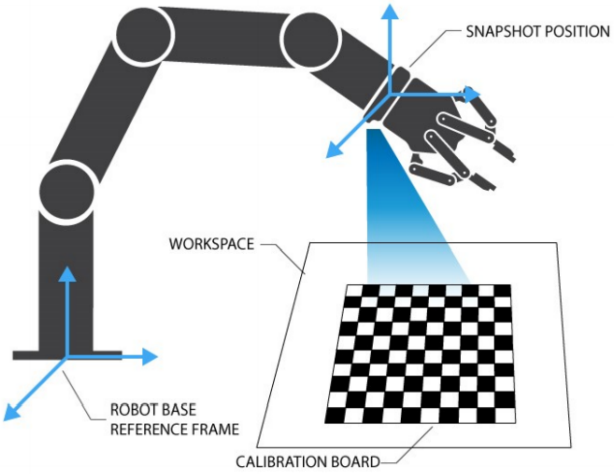


Figure 5.7: Camera calibration [42].

After the calibration, since the accessories represent an extension of the robot arm, some configurations need to be changed to guarantee the exact end of the tool for the robot program. From the beginning of the installation until calibrate the accessories, it took 3 hours.

5.3 Camera vision system

After this step, the next was to test and configure the vision system to recognize the piece. For this, the software has three different ways to detect objects. The first is automatic detection (recommended for irregular objects), the second is to detect objects with regular shapes like squares, rectangles, circles, and the third is using cad files.

For the first method, the vision system recognizes the edges and learns how the piece is. It first takes four pictures of the object, turning it 90 for each one. Later the robot starts scanning the piece by taking pictures from different angles of it. With this, in the end, it will have the object design to recognize it. The second method is just to enter the object's dimensions, but, as said before, it needs to be regular. Furthermore, the third recognizes the object by uploading the DFX file from the upper view and the piece height. This can be used by objects that have a 3D model and preferentially a flat upper surface for reducing the number of edges.

The piece used in the project does not have a flat surface on the top, a regular geometry, and is made by a metallic material, making the piece have reflexes. It has an almost circular shape with a straight line representing the opening that will be used for grabbing the piece, also on the surface, there are three circles and a crease. So these elements may interfere with the vision system. For the characteristics of each method, the second is already discarded. The first tests were made with the automatic method. After the system gets the first picture, it can choose which areas to keep in the recognition and which eliminate. Each color-difference the software recognizes as an edge. So, having a reflexive material, there were more edges than the real model.

The green areas in Figure 5.8 are the desired features to keep in the recognition. Each blue line is an edge of the model.

After this, were made two different recognition tests. One only with the edges of the external contours and another with the other characteristics, like the circles and the

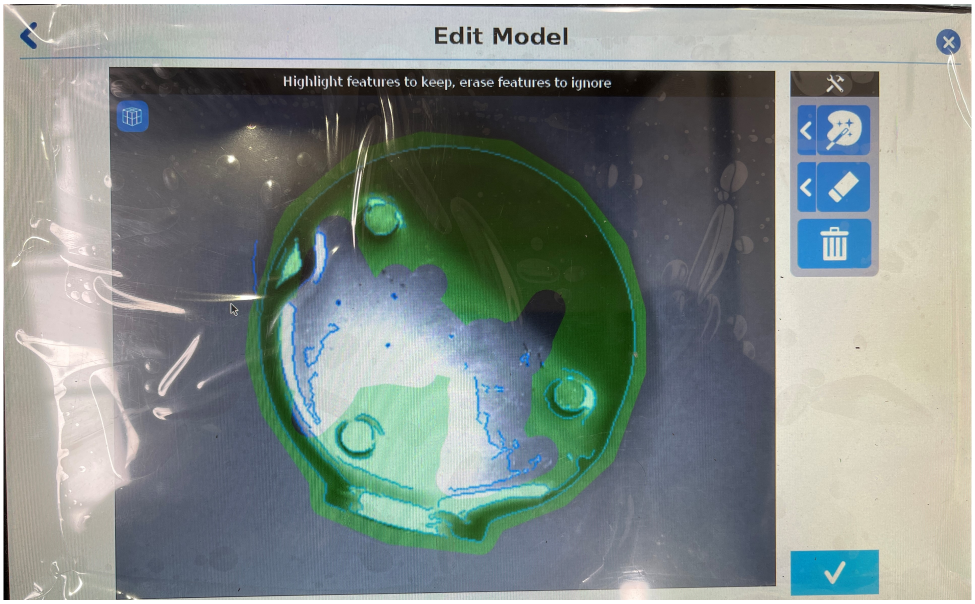


Figure 5.8: Editing model for recognition.

other crease. When the system recognizes how the model is, it is saved a base position of the trained model. This position is used to identify the piece's location and orientation. Later, some movements were set that were relative to this piece position. The movement sequence was to place the gripper inside the piece and grab it. These movements use the piece position as reference, so, for the following locations, they will be made to the piece position, every time moving to the same position in the piece.

For the first two tests, the one with more details of the piece represented a better recognition because the other details helped find the correct opening position. Recognizing only the external edges sometimes had some problems with the shadow. So the piece may be recognized in the wrong position.

The Figures 5.9 and 5.10 display the scores of the recognition in the corners of the camera's field of view. They are 62 and 63, respectively. With this, the acceptable values are set to 60, leaving a margin to recognition. This values are not so high due to the large amount of edges, that can slightly vary according to the orientation or illumination.

Another available feature for the system is the color recognition. For this, it is needed to highlight the piece, like in Figure 5.8, but now the whole piece. With a contrasting

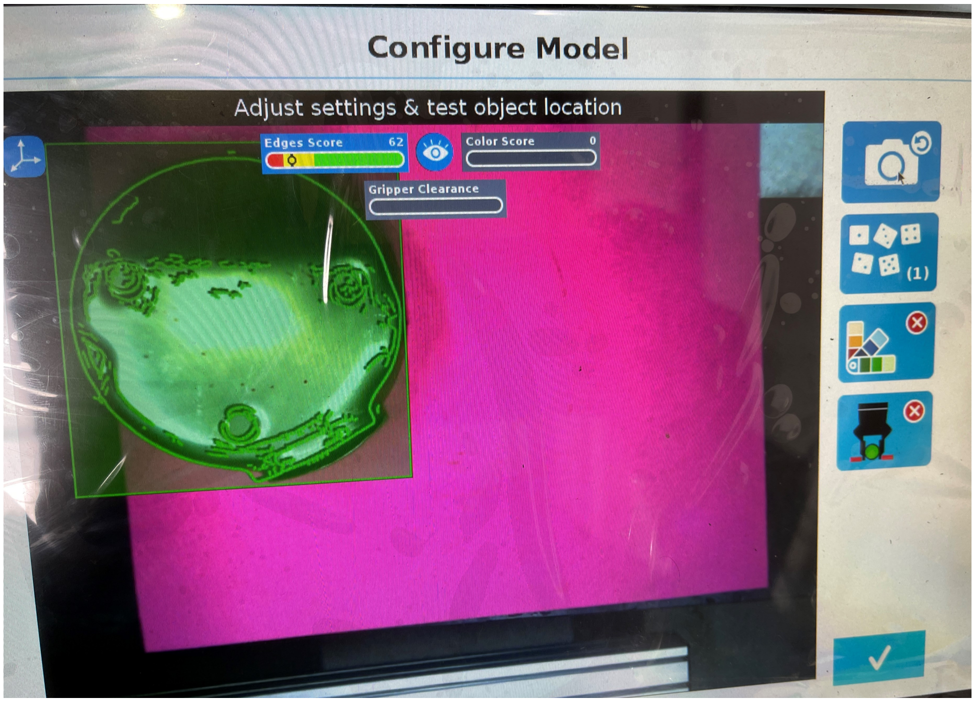


Figure 5.9: Evaluation piece recognition.

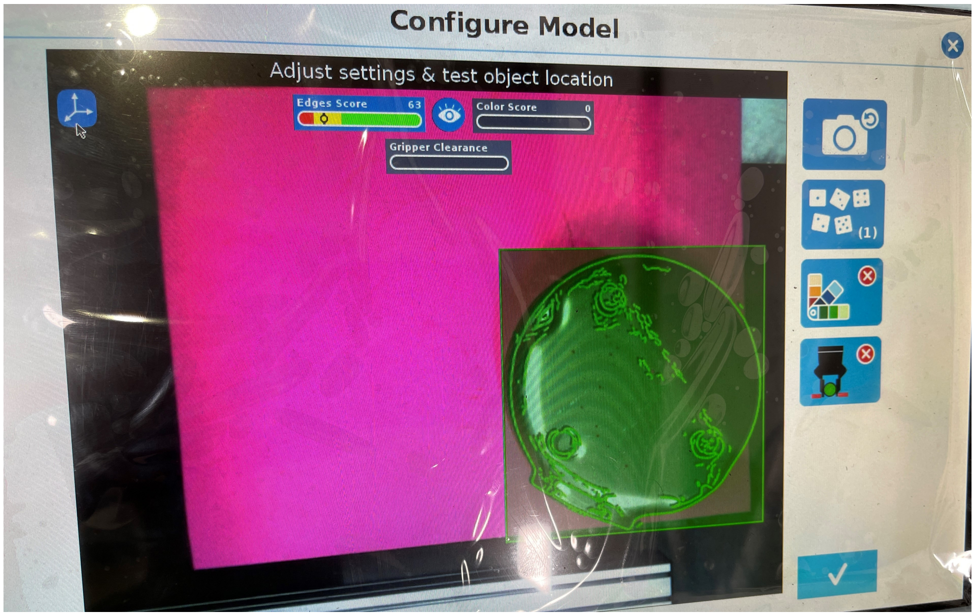


Figure 5.10: Evaluation of piece recognition.

background, the score for this feature can be very high, as seen in Figure 5.11 with a result of 99 of 100. Also, in this Figure, with the piece positioned in the center of the camera, the edge's score is higher (85).

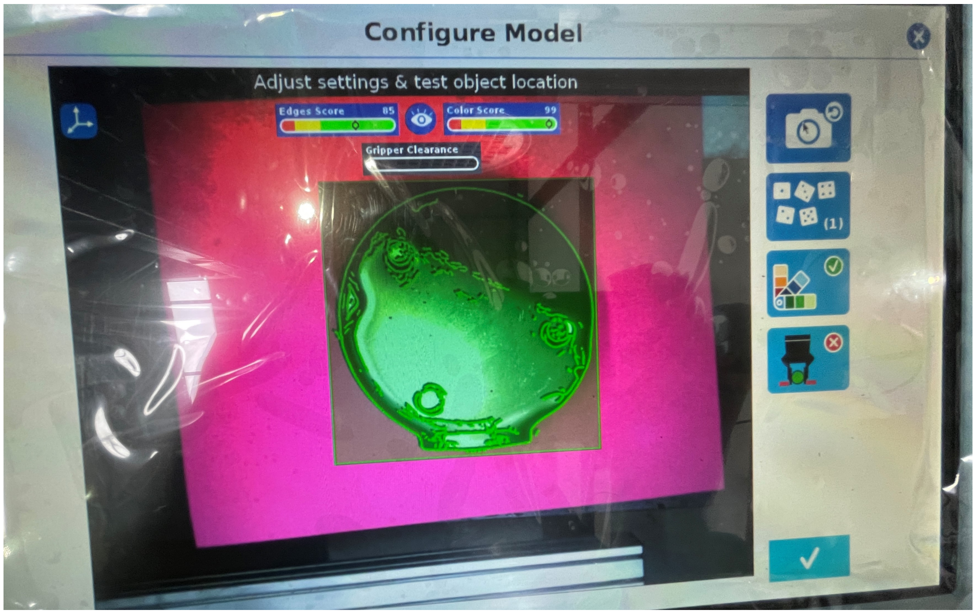


Figure 5.11: Using color validation.

The other method did not have good results because the edges of the file were in different heights, so for the system recognize the piece's correct height position was too complicated, and the results were not as expected.

At this time, the robot could recognize the piece position and grab it for successive movements. This implementation process, which consists of teaching the robot the piece model, recognizing it, and doing the movements, took around 3 hours too. This time was to make the tests, verify which was the best method, try and change the number of edges.

5.4 Development of new gripper fingers

Even though the robot recognized the piece, it sometimes hit the piece and not correctly entered the hole to grab it. This was happening because the gripper's finger dimensions were too close to the object opening. There was only a margin of 4 mm to enter in it, so not much space, as seen in Figure 5.12.

To correct it and make the system more accurate, was developed a new finger to the gripper. Once it was built in a 3D printer, it was easier to make a new one. So, a new

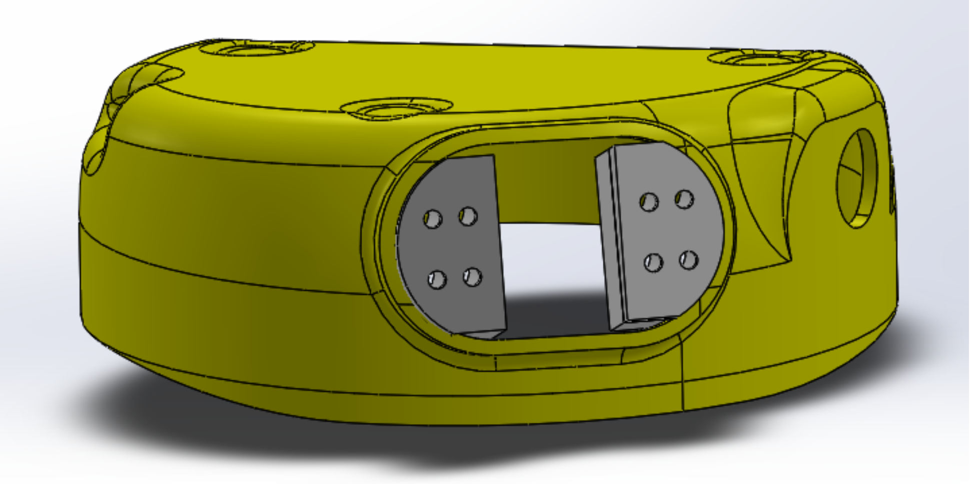


Figure 5.12: How the first developed finger will be in the piece.

model was designed just reducing the dimensions from 34 mm to 25 mm. With this, the system became more precise because the free space went from 4 mm to 13 mm, as seen in Figure 5.13.

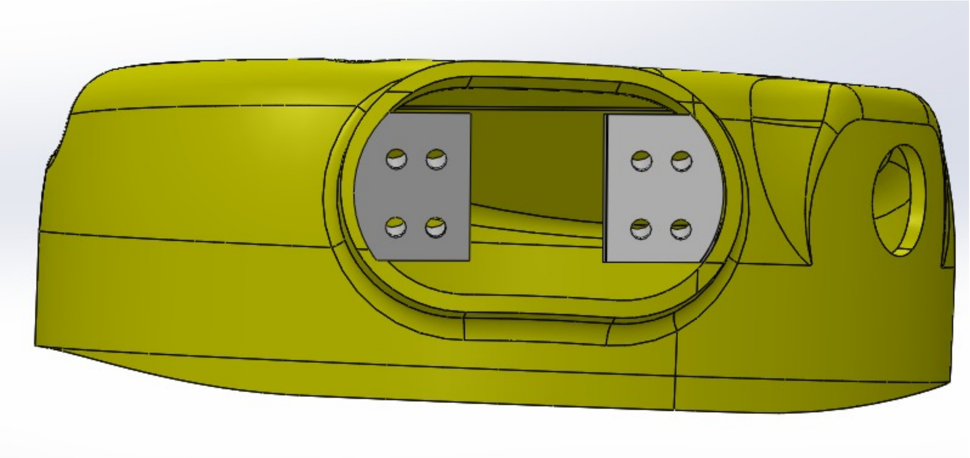


Figure 5.13: How the new finger will be in the piece.

With the newly designed finger, the system became more robust with more space and performed fewer failures.

5.5 Pallet solution

The last step for the tests was to palletize the pieces in the output box. If it was to palletize boxes, the controller already has a built-in function where it is needed to enter the four corners and the box height. With this, it will already recognize the pattern and perform it. This function worked by teaching the robot a center position in the pallet, the approach position, and the exit position for only the reference box. So, for the next ones, it would make the relative movement. However, there was a problem for the studied case: the pieces could not be placed in the same orientation because of the box size. So they should be put in different orientations to fit the output model best.

Also, there was another condition that the pieces must be positioned with the concavity faced down. After leaving the station, they will be washed, and with the concavity up, it would retain an amount of liquid in between that is not allowed and could damage them. With this was studied three ideas to place the pieces.

The first idea is shown in Figure 5.14 and could place 26. In the three cases, the bottom of the picture is where the robot is, and the left close to the calibration machine, as seen in Figure 3.9.

In the figure, the yellow spaces are empty. The unused locations would be left empty, or some pieces would be placed there, with the opening (where the robot attaches it) faced up. The design for each layout was developed according to the robot movements, and the empty spaces were needed for it to exit without damage. This solution was the one with fewer pieces because they were being placed only following the lines until the robot was not able anymore. The next idea could fit 31 pieces, and it is seen in Figure 5.15.

In this case, the pieces could not be placed all sequentially by filling one line and then the next, and so on. It would be needed to fill each line according to its approach and exit movement, so there needed to have a space for the circulation. Also, in this case, it is already seen that not all the lines have the same orientation. The two upper lines have the pieces facing the robot, the lower to the opposite direction, and the other two

Figure 5.14: First pallet solution.

are rotated 90° in relation to the first lines. In this configuration was less empty space than the first.

In order to try to place the largest number, the third layout was developed, which contains 33 and is like the Figure 5.16.

In this layout, the pieces from the two upper lines and the two lower were positioned almost pointing to the center, so with this was possible to place more pieces, reducing the empty spaces. Despite these four lines, one more contains five pieces, of which four are aligned to the calibration machine and the other on the opposite side.

5.6 Robot path programming

With the best result being the third layout, this was the chosen to be programmed. To program it, already knowing that the built-in function would not work, it was necessary

Figure 5.15: Second pallet solution.

to prepare a sequence for each piece. For this, a variable was used to count the piece number, starting by one, and a variable to count the pallet level, starting by zero. The positions in the pallet were declared as "LXCYtag", where X is the row number and C the column. The rows are counted from up to the bottom, so the furthest from the robot is 1, and the closest 4. The middle row is represented as "MYtag". Moreover, in both cases, Y is counted from right to left.

Having each point of the layout defined, they were all moved to a subprogram, so the sequence would not run to it, and the positions would still be available in the code. To perform the move sequence, the idea was to reach a reference point in the middle of the box and then move to a point up the desired position so that it could move linearly to the point. However, since the box has walls, if it were only these three movements, the robot would perform the rotation to align the piece to its next position during the movement, and for the most external pieces, this movement would hit the box. For avoiding it, the

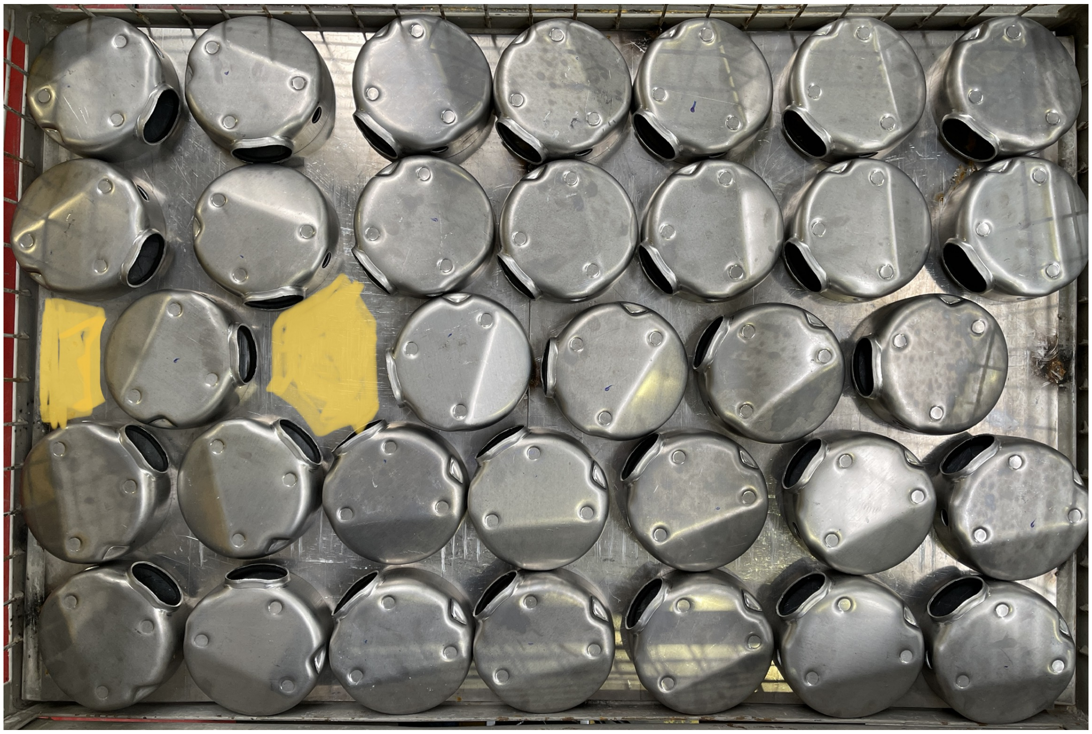


Figure 5.16: Third pallet solution.

solution was first to rotate and then move to the position.

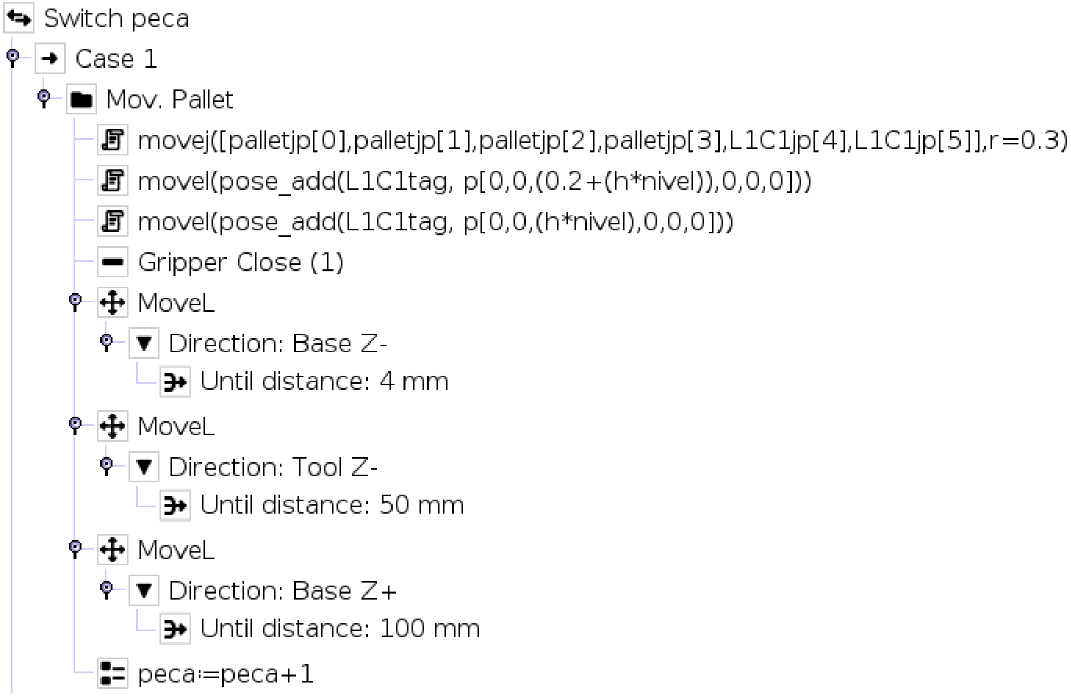
So, the robot in the reference position will align the piece to the next position and then move. The only way to do this was to use the robot's inverse kinematics for each point. The inverse kinematics is a vector of joint configuration coordinates that corresponds to a set of task space coordinates [43]. Therefore, it will have a vector of the six coordinates for each point, being the position 0 of it the base joint and the 5, the tool joint. The variables for each pose were declared as the position name adding "jp" to the end, referring to joint position.

To make the robot rotate, only the last joints were used in the script function of the controller. This function allows writing the code using programming language C5 without needing to use the built-in functions. One of the script functions is the "movej". This makes the robot movement linearly in joint space, which moves with less effort to the joints. The parameters of it are [44]:

- q: joint positions (q can also be specified as a pose, then inverse kinematics is used to calculate the corresponding joint positions).

- a: joint acceleration of leading axis [rad/s^2] (default = 1.4).
- v: joint speed of leading axis [rad/s] (default = 1.05).
- t: time [s] (default = 0).
- r: blend radius [m] (default = 0).

With this, having the inverse kinematics for each pallet point and the reference point, and knowing that those are vectors that can be accessed by typing the desired position of it, performing the referred movement, the structure used is shown in Figure 5.17.



```
Switch peca
  Case 1
    Mov. Pallet
      movej([palletjp[0],palletjp[1],palletjp[2],palletjp[3],L1C1jp[4],L1C1jp[5]],r=0.3)
      movel(pose_add(L1C1tag, p[0,0,(0.2+(h*nivel)),0,0,0]))
      movel(pose_add(L1C1tag, p[0,0,(h*nivel),0,0,0]))
      Gripper Close (1)
      MoveL
        Direction: Base Z-
          Until distance: 4 mm
      MoveL
        Direction: Tool Z-
          Until distance: 50 mm
      MoveL
        Direction: Base Z+
          Until distance: 100 mm
      peca:=peca+1
```

Figure 5.17: Program sequence for each piece.

In this sequence is possible to notice that the case for each piece has a “movej" where the first four joints are relative to the reference point and the last two to the desired point, using a blend radius of 30 cm. With this, the robot would move from the reference to the next, adjusting the last two joints in a radius of 30 cm, saving time between the movements.

After this adjustment, the following point is 20 cm above the desired position. This would make the robot approach the point and move only in the Z-axis next, avoiding hitting anything. The movement to this pose is a “movel". The difference between this and the last is that this moves linearly in space, so there would be a straight line between the two points. The option to use this is to avoid any joint move that would result in the piece colliding with the box walls.

In the pose, just like on its approach, is used the function “pose_add". This is used to add a pose to another, and the sum made is not using a pose but to perform an offset. The added pose is a pose vector ([x, y, z, rx, ry, rz] - the position in the three-axis [m] and the orientation [rad] relative to each) that only has a change in the z-axis. This adds an equation h*nivel, where “h” is the piece height, and “nivel” is the level that is being palletized. I.e., it is the first piece, so the level is 0. With this, there would be no addition to the final pose, but if it is the first piece from the second level ($nivel = 1$), it would be added h to the pose, and so on.

When the robot places the piece, it closes the gripper and moves 4 mm in the base Z direction, moving closer to the box surface. This movement, due to the piece opening inclination, prevents the robot from dragging it when leaving. Then, it moves in the tool Z- direction 50 mm. This direction is relative to the end of the gripper, where Z+ is perpendicular to the tool end plane. So the robot would place the piece, close the gripper, move a little down, then move out of the piece and then, the last movement, move linearly up 100 mm.

After ending the movements, it is added one to the piece variable. So the next move will be the next piece case. Also, in the last piece is set one more on level (*nivel*), and the piece is set back to one.

The specified moves allow the robot to place the piece at the marked points, which were points relative to the base. This would need that every time the box was changed, the next one would have to be placed in the exact same place. Otherwise, the robot would not place the pieces in the correct position.

5.7 Increasing the system robustness

To avoid this and make the system more flexible was used a visual offset. This function is available in the camera software that consists of using a tag, provided with the accessory, that will be used as the base to all the points. For this, it is necessary to place this tag on the box, and every time it is going to begin the movements for a new storage sequence, the robot should recognize where it is to perform the correct movements. Thus the pieces will always be in the same place inside the box. This system allows to recognize the linear displacement of the pallet and the orientation, i.e., even if the box is slightly rotated, it will still position the right way in the box surface.

Since there would have to keep moving the tag from one box to the other, it is necessary to place it in the same position. To guarantee it was developed a structure that would fit in the box corner. Once all the boxes have the same design and have a characteristic that is a thin wall on the top edges, this support will be placed there. The model developed is show in Figures 5.18 and 5.19.

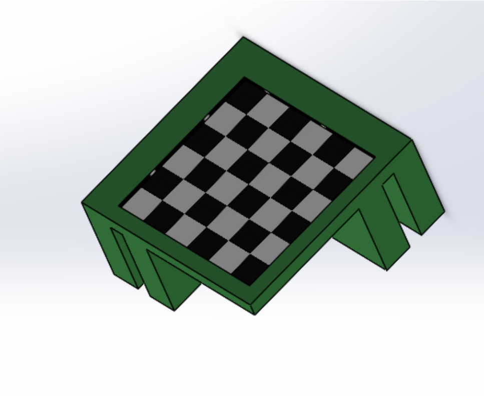


Figure 5.18: 3D model of the tag support.

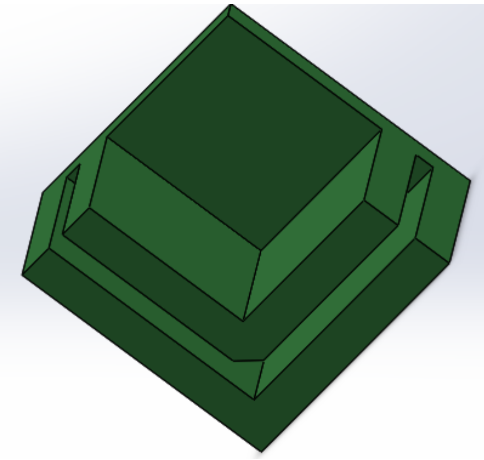


Figure 5.19: Other view of the 3D model of the tag support.

In the Figures, the green part is which is printed in a 3D printer, and the chessboard represents the tag, that is seen in Figure 5.20.

Using the camera and the tag showed in Figure 5.20 the system would be able to perform the described solution.

Figure 5.20: Robot and the visual offset tag

Since the camera system may sometimes fail, a loop was added in the code using the force sensor and the detection to avoid the robot performing the cycle without any piece. The force system can identify if the gripper is grabbing any object and the distance between the fingers. When the piece is attached to it, the opening is 22 mm, so was set a distance of 22 ± 2 mm.

If the piece is not correctly picked or not even detected by the force sensor, the system will restart until it precisely grabs it. Another feature used was to check if the vision system detected the piece. If the output was null, it would restart and try to find again.

5.8 Automating an environment not designed for automation

One of the main issues in developing this solution is that the whole system was not designed to be automated. Many points in the system difficult the study and make it hard to find the solution. A cobot is designed to be easy to program. And it is. However, for well-designed plants, this works better. The main problems of this case were:

- Available work space inside the calibration machine.
- Piece design.
- Box design.

The first was the one that made the picking area in the piece be in the front. Otherwise, it would not be possible to place it inside. The second and the third interfere in the same thing: the palletizing solution. For rectangular boxes, it is possible to use built-in functions where it is only needed to set the four corners, the approach and exit movement, and the box dimensions. With only this, it would place all the boxes correctly in only a few minutes. Even if it was not a box, but if it could pick the piece from the top, it would be possible to use this.

Also, the piece shape makes it possible for one to be placed inside the other. This first implied in a complex and laborious solution to pick from the input box and next in the palletizing, once the place that they were left, could not be the place where them will be. At least, this is not a problem for the company, but if the piece moves down, the next, the robot will leave it in an area without contact with other parts.

Another problem relative to the shape is that, because the next stage is washing, the pieces need to be with the concavity faced down to avoid a liquid accumulation.

The system needs the camera to recognize the position and orientation because they do not always come in the same place, adding time in the cycle. Also, the box walls needed the robot to perform one movement more to avoid contact.

If the layout did not have these peculiarities, the implementation would have been faster, and also the program would have much fewer lines. I.e., the built-in pallet solution has around 20 - 25 lines and for the actual was needed to set each position (34 lines), each inverse kinematic variable (34 lines) and also a case for each, like Figure 5.17 (16 lines per case).

Chapter 6

Conclusions and future works

This work addressed the use of collaborative robots inserted into production lines, highlighting the approach used to insert a cobot into a line that is in operation.

The problem studied in this work is related to the need to develop a robotic solution to automate an industrial process. This process initially considers the two machines located in two different places, so the employees must do the tasks in the first machine for a time. Then they would have accumulated several pieces for further move those pieces to the next station (i.e., calibration). With a significant quantity of parts, the employee would stay in front of this machine, placing the piece inside the machine and lately palletizing it. This waiting time to have a certain quantity of parts ready for the second machine was a lost time because must wait this whole time for only then move to the next. The starting production was of 1600 parts per shift.

After the first studies, the two machines were placed in the exact location, being now adjacent inside the station. Then, through simulations, was studied the best scenario to develop an automated solution. Were three: one transiting robot between the two stations, one robot for each station, and a hybrid solution composed of a robot and a human.

The company decided by the third option on behalf of its cost-benefit (a difference of 1.25 % in production related to the second but one less robot and does not need the investment to automate picking pieces from the initial pallet), increasing the actual production in 553 parts per shift. They intended to have a collaborative robot. With the specified requirements, the robot was acquired and implemented.

The implementation was done with all the hardware installation and software configuration, configuring the vision system to recognize the piece and its position and orientation to attach correctly. Afterward, was tested the path movements and studied a solution to have the most significant amount of parts in the output boxes, needing to code one case for each position to attend this request.

Besides those points, some approaches were developed to increase the robustness of the system. Reducing the gripper fingers width to better fit in the object's opening, using the available force sensor to detect if the piece is correctly attached, and use a tag to find the correct box position.

The significant difficulty during the development was automating a station that was not prepared for it. Many steps could have been shortened if it was a proper cell, with vast space for the robot to move, access, and leave the machines, an appropriate pallet solution, possibly with guides to the pieces, remaining them at the desired position.

After the development, the Catraport director, Umberto Pellegri, conceded his statement about the work and all the process engaged.

"*The first time I had the idea to get IPB involved in this project came during a visit to their CeDRI Lab where they have installed a Collaborative Robot. I'm a fan of new technologies, but at the same time I strongly believe in the centrality of the humans in all the Industrial process, so to see how a Collaborative Robot could work safely together with a person and help to increase the productivity and lower the ergonomic efforts required to a person to do certain operations was for me a great opportunity. At that time we had the described operation still very badly designed in terms of Lean Manufacturing and the first approaches made by Heitor to design a solution made me think to arrange a layout able to assure the one piece flow and avoid all the waste of intermediate stocks. Then the different simulations done and the comparisons and analysis of them, helped me to get to the optimized solution which was the interaction between a person and a Collaborative Robot. After this phase, Heitor gave his best during the actual implementation of the* *solution, in fact through the research and the analysis of a lot of case studies available in the library he came up with very clever solution presented in the thesis as the use of an identificatory for the position of the GITTERBOX, the optimization of the movements of the arm and also the optimization of the disposition of the parts inside the GITTERBOX. I strongly believe that the perfect match between the theory learned during his studies and the skills he developed during the challenge he faced in a real implementation made him grow and get ready for the future. By reading his thesis, I remembered all the steps done together, the enthusiasm he demonstrated in all the situations and also his gradual growth in the role he was having in the project, from the first timid steps to the confidence and independence of the last part of the implementation. A big thanks for this successful implementation to Heitor and of course Paulo, Luis and all the CeDRI team who helped to develop this fantastic solution."*

Regarding future works, several possibilities can be exploited to improve the solution proposed in this work. To finish the robot's implementation by placing the cobot in the production line and adjust the position to the real machines. Later, implement the communication between the devices and the robot. For this, obtain the input and output signal voltages of the calibration machine and a sensor to identify when there is a piece at the end of the Omera machine. With these, connect them to the robot's controller and define them as digital input or output to increase these features in the code. After the integration, optimize the cycle time. In this task will be removed unnecessary steps, shortened some movements, and fixed artificial lightning at the end of Omera to guarantee the same illumination to every piece. So it will be able to use a steady configuration to the camera without needing autofocus or auto-brightness.

With the provided data from the robot's camera, perform image processing to capture defects during production, avoiding its propagation. For this, use the OpenCV tool to process the images obtained from the parts produced. Create a machine learning model with the library TensorFlow departing from a pre-trained model to identify visible common defects like hazards, cracks, or stains.

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